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THE PYRITE—MARCASITE RELATION

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ABSTRACT

The control of the precipitation of pyrite and marcasite by chemical environment suggests that these two minerals are not a dimorphous pair in the usual sense of the term, but rather that they are chemically distinct compounds. A critical study of all available analyses indicates that pyrite corresponds very closely to ideal FeS_2, but that marcasite is definitely sulfur-low. Allen and Johnston's precision analyses of these two minerals, using identical procedures on each, also bears out this conclusion. Marcasite is thus a compound somewhat more iron-rich than FeS_2, just as its isomorphous arsenic analogue, löllingite, is a compound usually somewhat more iron-rich than $FeAs_2$. The phase boundary between pyrite and marcasite is, therefore, analogous to a phase boundary in, say, the Cu-Zn (brass) system, with crystal structure a function of chemical composition. At ordinary temperatures, the boundary between marcasite and pyrite is close to the composition FeS_2, which gives rise to the probable misconception that both are exactly FeS_2. The excess iron in marcasite and löllingite can be accommodated in the crystal structure in only one simple way out of three possibilities: interstitial solid solution, omission solid solution or proxy solid solution. These three cases are distinguishable by comparing the unit cell densities with the experimentally determined densities. Proof is given that in löllingite and marcasite, the excess iron is due to proxy solid solution, which indicates the corresponding chemical formulas of these minerals to be:

$$\text{löllingite: } Fe \left|\begin{matrix} Fe \\ As \end{matrix}\right|_2 \qquad \text{marcasite: } Fe \left|\begin{matrix} Fe \\ S \end{matrix}\right|_2$$

The chemical difference between pyrite and marcasite provides a ready explanation for preferential formation of marcasite in acid solution as against the formation of pyrite in alkaline solution. The function of the hydrogen ion seems to be to remove some of the S from the normal FeS_2 groups to form H_2S and sulfur-deficient-FeS_2, which is marcasite.

INTRODUCTION

Pyrite and marcasite have long been regarded as two different forms of the same chemical compound, FeS_2, an opinion which has been largely consolidated by several publications of the Geophysi-

cal Laboratory.[1,2] In addition to placing pyrite and marcasite definitely in the category of polymorphous pairs, with marcasite as the unstable member under ordinary conditions, investigations of that laboratory have also established the following important fact: Acid solutions and low temperatures favor the precipitation of marcasite, while alkaline solutions and high temperatures, on the other hand, favor the precipitation of pyrite. At a given temperature, the proportion of FeS_2 precipitating as marcasite is an almost linear function of the final acid concentration.

This is held to be an example of the theory that the external chemical environment can affect the nature of the phase precipitated, for Allen, Crenshaw, Johnston, and Larsen[3] say, in explanation,

> Monotropic forms often crystallize from some particular solvent. . . .

The particular solvent, in this case, differs from the one which precipitates the stable modification by the hydrogen ion contribution of a half per cent, or less, of sulfuric acid, or of a quarter per cent, or less, of hydrochloric acid. Furthermore, the unstable marcasite will precipitate even in the presence of the stable modification, pyrite, provided that the acid concentration is right. In nature, cases are known of the unstable marcasite growing in parallel position on the stable pyrite.[4]

It is natural to entertain the suspicion that this group of conditions contains elements which do not fit into a consistent system. One could understand the situation much more readily if pyrite and marcasite were not polymorphous forms but were actually chemically distinct. It is easy to understand why a slight difference of chemical environment should condition the precipitation of chemically distinct compounds, but it requires a rather elaborate pyramiding of theories and hypotheses to explain why an insignificant change in the chemical environment would change the physical modification of a precipitating compound.

This objection may be summarized semiformally as follows: There are two propositions:

[1] E. T. Allen, J. L. Crenshaw, John Johnston and Esper S. Larsen, The Mineral Sulphides of Iron: *Am. J. Sc.*, (4) **33**, pp. 169–236, 1912.

[2] E. T. Allen, J. L. Crenshaw, and H. E. Merwin, Effect of Temperature and Acidity in the Formation of Marcasite (FeS_2) and Wurtzite (ZnS); A Contribution to the Genesis of Unstable Forms: *Am. J. Sc.*, (4) **38**, pp. 393–431, 1914.

[3] Reference 1, p. 190.

[4] Victor Goldschmidt, Atlas der Krystallformen, Heidelberg, 1920, Vol. 6, figs. 107 and 118.

1. Pyrite and marcasite are polymorphous forms of FeS_2, of which pyrite is the stable modification under ordinary conditions.
2. Pyrite and marcasite are precipitated together, the proportion of the marcasite present being proportional to the hydrogen ion concentration, the maximum absolute value of which is very low.

One chooses, arbitrarily, let us say, to doubt that these form a consistent body of facts. He is then confronted by three alternatives:

(a) 1 is in error.
(b) 2 is in error.
(c) Both 1 and 2 are in error.

There is no reason to doubt the careful work of the investigators of the Geophysical laboratory with regard to 2. Therefore all alternatives except (a) are eliminated.

The present paper has as its theme, an inquiry into possible support for the proposition that pyrite and marcasite are chemically distinct, and the consequences of the results.

The Composition of Pyrite and Marcasite

In considering the possible variations in composition of pyrite and marcasite from the ideal FeS_2 formula, and realizing how impure minerals almost universally are, one might very naturally be lead to look for impurities in one or the other, or at least different impurities in pyrite than in marcasite, in nature, as a possible cause of the difference in modification. It will appear, as a matter of fact, that impurities are a factor in so determining the modification to precipitate. At the present stage of the inquiry, however, the guiding principle must be that as many variables as possible should be eliminated from the problem in order to gain a clue to the fundamentals of the situation. In this connection, it will be recalled that the investigators of the Geophysical Laboratory worked with as pure preparations as laboratory conditions permitted, and still were able to produce pyrite or marcasite at will. As a start then, one only need consider the variations possible in the system iron-sulfur. The writer has therefore studied analyses of pyrite and marcasite which contain only iron and sulfur. Most of the analyses are taken from Doelter's compilations.[5]

[5] C. Doelter and H. Leitmeier, Handbuch der Mineralchemie, IV, Erste Hälfte, **1926**, pp. 527–529; pp. 566–567.

TABLE I. ANALYSES OF PURE IRON-SULFUR PYRITE (arranged according to date of publication)

No.	Locality	Source	Remarks	Weight per cent				Atomic per cent		Atomic ratio
				Fe	S	*Other*	*Total*	Fe	S	$\frac{Fe}{S}$
1.	Phillippshoffnung near Siegin	K. Schnabel, through C. F. Rammelsberg, *Mineralchem.*, **4**, Suppl. 198, 1849. (*Doelter*, **1**, p. 527)	Massive	46.53	53.39	—	99.92	.833	1.665	$\frac{1}{2.000}$
2.	Heinrichssegen near Müsen	" (*Doelter*, **2**, p. 527)	Crystals	46.50	53.50	—	100.00	.833	1.669	$\frac{1}{2.001}$
3.	Tuscany	C. v. Hauer, *Sitzb. Wiener Ak.*, **12**, 287, 1854. (*Doelter*, **14**, p. 528)	Pyritohedrons d=4.925	45.53	53.37	1.10 (Insoluble)	100.00	.815	1.664	$\frac{1}{2.040}$
4.	Elba	Mène, Pyr. d. fer., 1867, through A. d'Achiardi, *Min. Tosc.* **2**, 321, 1873. (*Doelter*, **17**, p. 528)		43.50	52.20	4.10 (Insoluble)	99.80	.779	1.628	$\frac{1}{2.090}$
5.	Monte Amiata, Tuscany	J. F. Williams, *N. Jb. Min., Beil. Bd.* **5**, 430, 1887. (*Doelter*, **18**, p. 528)		48.78	46.95	—	95.73	.874	1.465	$\frac{1}{1.677}$

TABLE I (continued). ANALYSES OF PURE IRON-SULFUR PYRITE (arranged according to date of publication)

6.	Wattegama, Ceylon	C. Schiffer, *Diss. München*, **5**, 1900. (*Doelter*, **20**, p. 528)	In the dolomite	44.99	53.79	1.22 (Insoluble)	100.00	.8045	1.676	$\frac{1}{2.085}$
7.	Miniera di Casall, Prov. Grosseto	G. De Angelis d'Ossat. *R. Acc. d. Linc.*, **11**, 548, 1902. (*Doelter*, **21**, p. 528)		47.10	52.97	—	100.07	.843	1.652	$\frac{1}{1.960}$
8.	Paraña, Brasil	C. v. John and C. F. Eichleiter, *J. k. k. geol. R. A.*, **53**, 481, 1903. (*Doelter*, **24**, p. 528)		46.84	51.97	0.52 (SiO_2)	99.33	.839	1.620	$\frac{1}{1.933}$
9.	Central City-Mine, Gilpin Co., Colorado	E. H. Kraus and I. D. Scott, *Z. Krist.*, **44**, 148, 1908. (*Doelter*, **25**, p. 529)	Crystals	46.51	53.26	0.59 (SiO_2)	100.36	.833	1.661	$\frac{1}{1.994}$
10.	Colorado	E. H. Kraus and I. D. Scott, *Z. Krist.*, **44**, p. 153. (*Doelter*, **29**, p. 529)	Well formed crystals free from impurity; no trace of Ni, Co, As, Sb, or Au.	46.31	53.06	0.54 (SiO_2	99.91	.829	1.656	$\frac{1}{1.998}$

TABLE I (continued). ANALYSES OF PURE IRON-SULFUR PYRITE (arranged according to date of publication)

No.	Locality	Source	Remarks	Weight per cent				Atomic per cent		Atomic ratio
				Fe	S	*Other*	*Total*	Fe	S	$\frac{Fe}{S}$
11.	Colorado	E. H. Kraus and I. D. Scott, *Z. Krist.*, **44**, 153, 1908. (*Doelter*, **30**, p. 529)	Well formed crystals free from impurity; no trace of Ni, Co, As, Sb, or Au.	46.39	53.11	0.52 (SiO_2)	100.02	.830	1.657	$\frac{1}{1.997}$
12.	Colorado	" (*Doelter*, **31**, p. 529)	Well formed crystals free from impurity; no trace of Ni, Co, As, Sb, or Au.	46.35	53.08	0.53 (SiO_2)	99.96	.830	1.656	$\frac{1}{1.996}$
13.	Elba	E. Arbeiter, *Diss. Breslau*, 1913, 1. (*Doelter*, **39**, p. 529)		47.00	52.50	—	99.50	.841	1.637	$\frac{1}{1.947}$
14.	Elba	E. T. Allen, J. L. Crenshaw, and J. Johnston. *Z. Anorg. Chem.*, **76**, 210, 1912. (*Doelter*, **40**, p. 529)	No impurities	46.49	53.49	0.04 (SiO_2)	100.02	.832	1.669	$\frac{1}{2.003}$

Table I (continued). Analyses of Pure Iron-Sulfur Pyrite (arranged according to date of publication)

15.	Rio Tinto	K. Bornemann and O. Hengstenberg, *Metall und Erz*, **1920**, 344. (*Doelter*, **41**, p. 529)		46.20	52.81	1.00 (Insoluble)	100.01	.8275	1.649	$\frac{1}{1.991}$
16.	Locality unknown	Carmichael, *Univ. Toronto Studies, Geo. Series*, No. **22**, pp. 29–36, 1926.		46.52	52.70	0.40	99.62	.834	1.644	$\frac{1}{1.970}$
17.	Elba	Robert Juza and Wilhelm Biltz, *Zeit. Anorg. Chem.* **205**, 273–286, 1932.		46.69	52.97	0.09	99.75	.837	1.651	$\frac{1}{1.973}$
18.	"	"		46.62	53.14	0.08	99.84	.835	1.657	$\frac{1}{1.985}$
19.	U. S. A.	"	d=4.978	47.28	52.89	—	100.17	.847	1.652	$\frac{1}{1.950}$
20.	"	"	"	47.35	52.74	—	100.09	.848	1.645	$\frac{1}{1.940}$

TABLE II. ANALYSES OF PURE COBALTIFEROUS PYRITE (arranged according to date of publication)

No.	Locality	Source	Remarks	Weight per cent				Atomic per cent		Atomic ratio
				Fe Co	S	*Other*	*Total*	Fe Co	S	$\frac{Fe+Co}{S}$
21.	Franklin Furnace, N. J.	E. H. Kraus and I. D. Scott, *Z. Krist.*, **44**, 148, 1908. (*Doelter*, **26**, p. 529)	Crystals	45.12 1.19	53.34	0.02 (SiO_2)	99.67	.8075 .0202 .8277	1.663	$\frac{1}{2.010}$
22.	Franklin Furnace, N. J.	" (*Doelter*, **27**, p. 529)	Crystals	45.28 1.30	53.26	0.03 (SiO_2)	99.87	.811 .022 .833	1.661	$\frac{1}{1.994}$
23.	Franklin Furnace, N. J.	" (*Doelter*, **28**, p. 529)	Crystals	45.20 1.25	53.30	0.03 (SiO_2)	99.78	.809 .021 .830	1.662	$\frac{1}{2.001}$
24.	Locality unknown, (Probably Franklin Furnace, N. J.)	W. Vernadsky. *Centr. Min.* 495, 1914.		45.2 1.7	53.3	—	100.2	.809 .029 .838	1.662	$\frac{1}{1.987}$

TABLE III. ANALYSES OF PURE IRON-SULFUR MARCASITE (arranged according to date of publication)

No.	Locality	Source	Remarks	Weight per cent				Atomic per cent		Atomic ratio
				Fe	S	*Other*	*Total*	Fe	S	$\frac{Fe}{S}$
1.	Oxford clay near Hannover	H. Vogel and Reischauer, *N. Jb. Min.*, 676, **1855** (*Doelter*, **3**, p. 566)		46.90	52.70	—	99.60	.840	1.644	$\frac{1}{1.958}$
2.	Münstertal, Baden	Trapp, *Bg.-u. hütt Z*, **23**, 55, 1864. (*Doelter*, **4**, p. 566)		46.93	51.95	—	98.88	.840	1.620	$\frac{1}{1.929}$
3.	Jasper Co., Mo.	E. Arbeiter, *Diss. Breslau*, **11**, 1913. (*Doelter*, **8**, p. 567)	Chicken comb structure, surface greenish yellow, interior silver-grey.	46.55	53.05	As, Trace	99.60	.833	1.656	$\frac{1}{1.987}$
4.	Joplin, Mo.	E. T. Allen, J. L. Crenshaw, and J. Johnston, *Z. anorg. Chem.*, **76**, 210, 1912. (*Doelter*, **9**, p. 567)	Minute trace of Cu, only impurity	46.53	53.30	0.20 (SiO_2)	100.03	.833	1.663	$\frac{1}{1.995}$

TABLE III (continued). ANALYSES OF PURE IRON-SULFUR MARCASITE (arranged according to date of publication)

5.	Westfalia	Elfriede Ammermann, *Centr. Min.*, 577, 1924. (*Doelter*, **11**, p. 567)	Sulfur determination only	(47.38) by diff.	52.62	?	—	.848	1.641	$\frac{1}{1.936}$
6.	Macigno Calafuria, Tuscany	E. Manasse, *Atti. della Soc. Tosc. di. Sci. Nat., res. Pisa*, **21**, 159, 1905; *Z. Krist.*, **43**, 496, 1907. (*Doelter*, **12**, p. 567)		42.69	48.65	As, Trace FeO, 0.71 SO_3, 0.83 H_2O, 0.58 $BaSO_4$, 6.48	99.94	.764	1.517	$\frac{1}{1.985}$
7.	Hill near Osnabrück	M. Dittrich through Fr. Schöndorf and R. Schröder, 2. *Jahresber. Niedersächs, geol. Ver.* 152, **1909.** (*Doelter*, **13**, p. 567)		47.22	52.61	—	99.83	.846	1.641	$\frac{1}{1.941}$
8.	Loughborough Township, Ontario	Carmichael, *Univ. Toronto studies, Geol. Ser.* No. **22**, pp. 29–36, 1926.		46.56	53.40	0.05 (Insoluble)	100.01	.834	1.665	$\frac{1}{1.997}$

To Doelter's have been added those which have been mentioned since.

Table I lists the available analyses of pyrite containing (according to the analyses themselves) only iron and sulfur. Table II gives a set of excellent analyses of pure cobaltiferous pyrite, three of which are surely from Franklin Furnace while the fourth is so nearly identical to these that it may also be reasonably supposed to represent pyrite from the same locality, although the actual locality for this material is not given. Table III gives available analyses for marcasite containing no essential elements other than iron and sulfur.

The analyses have been reduced to iron and sulfur atom ratios, which are given in the last columns of the tables. The analyses may be easily studied by means of the graphical representation of all analyses given in figure 1. Here the analyses are plotted according to indicated iron-sulfur ratio, which should, of course, be 1/2.000 for ideal FeS_2

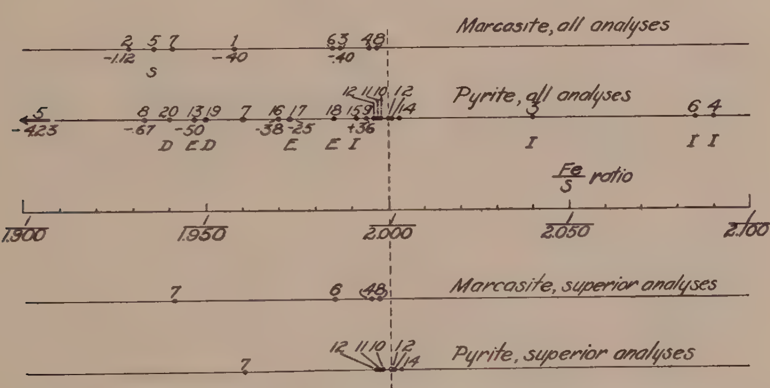

Fig. 1. Graphical representation of iron: sulfur ratios of marcasite and pyrite analyses. The iron content is arbitrarily considered constant while the sulfur content is taken as a variable. The notation beneath individual analyses is explained by the following key:

E = Elba pyrite, probably contaminated with hematite.
D = Subnormal density.
I = Contains insoluble material in excess of 1%.
S = Sulfur determination alone available, iron by difference.
−.67 = Percentage deviation of summation from 100.00%. (noted only in cases having notable deviation)

Pyrite. One notes that the pyrite analyses cover a considerable spread in iron-sulfur ratio. There is, however, a distinct tendency for the analyses to cluster densely about a value just a trifle lower than 1/2.000, with the rest of the analyses scattered in a group which also centers approximately here. This very strongly suggests a distribution of error about a correct value. That this is almost certainly the case is indicated by the following critical discussion of the analyses.

5. This analysis adds only to 95.73 and is obviously untrustworthy. In addition, the material for analysis is described as coming in thin leaves. The analysis may be summarily discarded.

8. This analysis is part of a routine report of a number of heterogeneous analyses, made, it would appear, by a firm of commercial analysts. There was no selection of material, but merely an analysis of a "pyrite" sample, which, incidentally, was a concretion. Whether the concretion was actually pyrite or marcasite cannot be ascertained. Newhouse,[6] as well as Van Horn and Van Horn,[7] have indicated that concretions may be of either mineral or both. Under any circumstances, this analysis is not one in which sufficient care has been exercised to warrant its inclusion among data to be used in establishing the composition of pyrite.

13, 17, and 18. These analyses represent Elba pyrite. The writer happens to be very familiar with this material from a search for fluid inclusions in pyrite. This particular material contains much hematite occurring as inclusions within single pyrite crystals. The lusters of the two minerals, although very different, blend very well on the conchoidally fractured surface of broken pyrite, which appears as intense yellow highlights and deep shadows. The hematite is therefore easily missed even though a search is made for it. Needless to say, included hematite would raise the apparent iron content of the pyrite. This is evidently just what has happened. Analysis 13 is accompanied by the statement: "with hematite, analysis free from same." The present writer doubts the latter statement. Analyses 17 and 18 are accompanied by the statement that the material "perhaps contains a little oxide," and the authors (chemists evidently), avoided the use of this material supposedly for this reason in their experimental work on the iron-sulfur system (using instead, however, pyrite which is probably just as questionable; see beyond). The list of analyses given in table I contains one by the Allen, Crenshaw and Johnston (No. 14) also of the Elba pyrite. This, if any, should be trustworthy, for it was published by men qualified both mineralogically and chemically to select and analyze minerals. It is noteworthy that this analysis is within the central region of pyrite iron-sulfur ratios. One can, therefore, discard the other Elba pyrite analyses as being very probably contaminated with hematite.

[6] W. H. Newhouse, Some Forms of Iron Sulphide Occurring in Coal and Other Sedimentary Rocks: *Journ. Geol.*, **35**, 1927, pp. 77 and 83.

[7] Frank R. Van Horn and Kent R. Van Horn, X-Ray Study of Pyrite or Marcasite Concretions in the Rocks of the Cleveland, Ohio, Quadrangles: *Am. Mineral.*, **18**, pp. 288–294, 1933.

19 and 20. The density of this pyrite, of unknown locality, "U. S. A.," is given as 4.978. In spite of Dana's generous range, this is too low for pyrite which ought to have a density of 5.02, according to Allen, Crenshaw, and Johnston. In view of the fact that the authors were evidently chemists, it seems fair to conclude that the high iron content and low density may not indicate an unusual pyrite (for certainly a higher-than-normal iron content ought to be accompanied by a high density), but rather indicate, say, pyrite plus some limonite-like alteration product, or possibly other contamination. Incidentally, the two (duplicate) analyses show a noteworthy variation of Fe:S of from 1:1.950 to 1:1.940. This is greater than the greatest deviation of any of the analyses of the central compact group of thoroughly trustworthy analyses, from their mean value. This indicates, then, either poor chemical manipulation, which is not very probable, or, irregular contamination of the samples, as from alteration products.

16. Carmichael has contributed a number of analyses of sulfides used in certain ore dressing tests. Analyses of both pyrite (locality unknown) and marcasite are included. (Incidentally, if the labels pyrite and marcasite were transferred on these two analyses, they would fit the groups of superior analyses very well.) As it stands, they form outposts beyond the superior analyses. This may be due, in the case of pyrite, to incomplete analysis, for the summation totals only 99.62%, which is a greater deviation from 100.00% than any unquestionably good analysis retained.

7. No obvious fault can be detected in this analysis.

3,4, and 6. These three analyses are exceptional in displaying *too great* a sulfur content. They are also exceptional in being the only pyrite analyses containing insoluble matter in excess of 1%, containing, 1.11%, 4.10%, and 1.22% insoluble. In analysis 3, this "insoluble" shows up by lowering the density to 4.925. The material was obviously contaminated in various ways and certainly unsuited to analysis. Numbers 3 and 6, incidentally, add to exactly 100.00, which makes it appear that some additional impurity was suspected and subtracted from the true experimental data.

This leaves a group of what might be termed superior analyses, published by such unimpeachable authorities as Kraus and Scott, and Allen, Crenshaw, and Johnston. There have been included two slightly doubtful analyses: one by Schnabel, which adds to exactly 100.00%, and therefore appears to have had some other original constituents which have been allowed for against the original data, and one by Bornemann and Hengstenberg, which contains the high amount of 1.00% insoluble. If these are omitted, the analyses constitute a consistent group with a maximum deviation of iron: sulfur ratio of less than half a per cent, the center of gravity of the group being just a trifle more iron-high than called for by the formula FeS_2. If the two analyses mentioned in this paragraph are retained, the group is extended about again as far as the previously-mentioned limit on the iron-high side. Although the theory to be presented by the writer is consistent with

either interpretation of the analyses, it is the writer's opinion that the slightly doubtful analyses be best omitted. This would give pyrite a composition close to, if not actually, FeS_2, with a possible very slight iron excess.

MARCASITE. There are all too few marcasite analyses available. A glance at Fig. 1, however, will indicate that all of these indicate an Fe:S ratio less than 1:2.000, without exception. Taken as a group, the analyses show less tendency to cluster about some well defined average value. Nevertheless, the group as a whole has an iron content distinctly greater than that of pyrite, the average of the group indicating a value somewhere in the region of 1:1.970, with several analyses clustered in the region of Fe:S = 1:1.985.

Analysis 2 does not add to near 100% and may be omitted from the list of superior analyses. Analysis 5, although it shows a significant deficiency of sulfur which should not escape attention, contains no direct determination for iron. Analyses 1 and 3 do not total to within 0.40% of 100%. But in spite of this fact, however, it is significant that if sulfur were added to them to the amount of the deficiency, analysis 1 would still not have enough sulfur to make FeS_2, and analysis 3 would have only just enough. This same sulfur handicap could be given other analyses of marcasite and still not make FeS_2.

The analyses by Allen, Crenshaw, and Johnston (No. 4), and the one by Manasse (No. 6) may be distinguished as distinctly superior, and these may be used with confidence in establishing a formula for marcasite. The one by Arbeiter (No. 3) also seems to have been done with some mineralogical responsibility, in spite of its somewhat low summation. These form a system of three good analyses which indicate an iron:sulfur ratio of from 1:1.985 to 1:1.995. These, as well as all the rest (except 2 and 5, which show such obvious internal grounds for rejection) are shown plotted in fig. 1.

COMPOSITIONS OF PYRITE AND MARCASITE. Figure 1 shows graphically that the composition of pyrite is very close to FeS_2, but may possibly run as low in sulfur as $FeS_{1.998}$. This conclusion may be subject to some extension with the appearance of further reliable analyses of pyrite. The figure also shows that marcasite runs preferably to a formula $FeS_{1.990}$, but may possibly vary somewhat, or even vary extensively—the data are not sufficiently numerous to decide on this point with any assurance—, but that

it only approaches the composition FeS_2. If Carmichael's analysis is excluded—and it seems obvious from her recorded data that an analysis comparable with the best complete mineralogical determination was not attempted for her ore dressing purposes—, one can say that no marcasite analysis has appeared which more than approaches the formula FeS_2, in some cases even with the handicap that all analytical deficiencies be conceded to be unapprehended sulfur.

This excess of iron in marcasite is quite unorthodox, but need not be regarded with surprise. The other well known member of the marcasite group, löllingite, $FeAs_2$, almost always runs to excess iron. Pure $FeAs_2$ contains 27.16% Fe and 72.84% As. A glance over pages 594, 595 and 596 of *Doelter's Handbuch* will show that the iron content of löllingite is usually higher than this value even making allowances for some of the arsenic being replaced by sulfur. This is well known and customarily explained by saying that the löllingite contains the "leucopyrite molecule," Fe_3As_4, in solid solution.

Precision Analyses of Pyrite and Marcasite. Since the analyses just discussed were not originally made with a view to determining a chemical difference between pyrite and marcasite, it would be desirable to have a series of comparable analyses of ideally pure minerals made with extreme care for this particular purpose. Fortunately, just such data are available for one occurrence of pyrite and one occurrence of marcasite. These have been provided by Allen and Johnston[8] who obtained them for quite a different purpose, namely, for tests of the precision character of iron and sulfur determinations in FeS_2. Their best determinations are those given as pyrite analysis 14, table I, and marcasite analysis 4, table III, above. The minerals were ideally pure except that the marcasite contained a trace of copper and that both minerals contained a slight admixture of quartz.

Not only does their best result show the marcasite to have a supernormal iron:sulfur ratio, but each of the sulfur determinations, made by different methods, show a lower sulfur content for marcasite than for pyrite. These determinations are as follows:

[8] E. T. Allen and John Johnston, The exact determination of sulphur in pyrite and marcasite: *Journ. Ind. and Eng. Chem.*, **2**, pp. 196–203, 1910.

	Pyrite	*Marcasite*
Allen and Johnston's method		
Sodium carbonate variation	53.46	**53.28**
Magnesium oxide variation	53.53%	**53.33%**
	53.49 Av.	**53.30** Av.
Fresenius's method modified	53.37	**53.13**
		53.11
		53.12 Av.
Lunge's method modified	53.18	**52.99**
		53.07
		53.03 Av.
Ideal FeS_2	53.44	

The lower determination of each comparable pair is given in block type. Note that the marcasite is always the lower, and that it is always less than the ideal value. It would appear that the low sulfur content of marcasite called forth the duplicate analyses for this mineral as compared with the single determinations for pyrite in the two last methods. The low sulfur content of marcasite, evidently, then, does not depend on the method of analysis.

Furthermore, the gravimetric determinations of iron gave higher iron for marcasite than for pyrite in each comparable determination. These are as follows, the higher iron content being indicated in block type:

	Pyrite	*Marcasite*
	46.46%	46.49%
	46.53	46.57
	46.49 Av.	**46.53** Av.
Ideal FeS_2	46.55%	

The volumetric determinations of iron were as follows:

Pyrite: 46.75, 46.67, 46.66, 46.75, average, 46.72%.
Marcasite: 46.63, 46.49, 46.54, average, 46.55%.

Unfortunately, the volumetric comparison does not tend in the same direction as the gravimetric. The authors, however, accept the gravimetric results as nearer the truth, especially in view of the fact that if the volumetric results were used, the totals would be 100.25% for pyrite and 100.05% for marcasite as against 100.02% for pyrite and 100.03% for marcasite in the gravimetric

determinations. The totals appear to indicate a false iron excess for pyrite in the volumetric determinations.

One may conclude, therefor, that not only does the statistical study of the pyrite and marcasite analyses give practically unanimous support to a higher iron:sulfur ratio in marcasite than in pyrite, but that the most carefully made individual determinations, using identical methods on both minerals, bear out the same thesis.

THE DISTRIBUTION OF EXCESS IRON IN THE MARCASITE GROUP.

LÖLLINGITE. In the discussion of what happens to the excess iron in the marcasite group of minerals, it will be convenient to start with löllingite, for in this mineral the effects are exaggerated and excellent data are available.

Löllingite may be conceived as having a high iron:arsenic ratio in only three simple ways:

1. The structure of the crystal is that of ideal $FeAs_2$, with additional iron atoms in the interstices, between other atoms in the normal structure. This may be termed *interstitial solid solution* and may be represented by the formula $FeAs_{2+n\,Fe}$, where n is a small fractional number indicating the iron excess.
2. The structure of the crystal is that of the ideal $FeAs_2$ with occasional arsenics missing in the structure. This is actually not a solid solution at all, but could not be distinguished from that general class of compounds by its analysis alone. For uniformity, however, this may be designated, *omission solid solution*, and represented by the formula $FeAs_{2-m}$, where m is a small fractional number indicating the arsenic deficiency.
3. The structure of the crystal is that of the ideal $FeAs_2$ with some of the arsenic atoms missing but with iron atoms proxying in their places. This may be represented by the formula $Fe\left|\begin{matrix}Fe_x\\As_{2-x}\end{matrix}\right|$, where x is a small fractional number indicating the number of iron atoms occupying the positions normally occupied by arsenic atoms. This condition may be designated *proxy solid solution.*

Complex solutions can also be imagined which involve combinations of the above cases. Case 1 gives rise to a supernormal density, because the unit cell has its normal contents plus additional iron.

Case 2 gives rise to a highly subnormal density because the unit cell has its normal contents less, on the average, a fraction of an arsenic atom. Case 3 gives rise to a slightly subnormal density in the case of löllingite (slightly supernormal in the case of marcasite), because the cell has its normal contents plus the loss in weight (gain in marcasite) accruing from replacing a fraction of an arsenic atom, on the average, by its equivalent in the lighter iron. From the cell dimensions as revealed by x-ray diffraction measurements, the known atomic weights of iron and arsenic, and the value of n, m, and x, as calculated from the chemical analysis, it is possible to calculate the mass per unit volume, or the density of the cell, which can then be compared with the actual measured density.

In the case of löllingite, excellent data are available for the use of the above criterion, in the published values of the constants of the Franklin Furnace crystals.[9,10]
These are as follows:

Chemical Analysis		Weight per cent	atom ratios	atomic per cent
	As	69.80	.933	1.76
	S	0.21	.007	0.013
	Fe	29.40	.530	1.00

Cell, containing 2 formula weights: $a = 2.85$Å
$b = 5.25$
$c = 5.92$
Volume $= 88.6$Å^3

The iron: arsenic + sulfur ratio is evidently much too high for ideal $FeAs_2$, so the excess iron must be allowed for according to either case 1, 2, or 3 above. These give the following results:

1. $Fe\left|\begin{matrix} As_{2-k} \\ S_k \end{matrix}\right| + nFe$, where n is determined by the condition: $\dfrac{1+n}{2} = \dfrac{1.000}{1.773}$

This gives $n = .0128$

Also $\dfrac{As+S}{S} = \dfrac{2}{k} = \dfrac{1.773}{.013}$, which gives $k = .015$

The formula is then $Fe\left|\begin{matrix} As\ 1.985 \\ S\ \ .015 \end{matrix}\right| + .128\ Fe.$

[9] L. H. Bauer and H. Berman, Löllingite from Franklin, New Jersey: *Am. Mineral.*, **12**, pp. 39–43, 1927.

[10] M. J. Buerger, The Crystal Structure of Löllingite, $FeAs_2$: *Zeit. Krist.*, **82**, pp. 165–187, 1932.

This corresponds to a formula weight of 213.3, which, substituted in the density relation $d=\dfrac{\text{mass of unit cell}}{\text{volume of unit cell}}=\dfrac{2\times 213.3\times 1.65\times 10^{-24}}{88.6\times 10^{-24}}$ leads to a density of 8.06

2. $FeAs_{2-m}$, is here, $FeAs_{1.76}\,S_{.013}$, which corresponds to a formula weight of 187.8.
   This leads to a density of 6.99

3. $Fe\left|\begin{matrix}Fe_x,\\ As_q\\ S_r\end{matrix}\right|$ where p, q, and r are determined by the conditions: $\begin{cases}\dfrac{1+x}{(q+r)}=\dfrac{1}{1.773}\\ x+(q+r)=2\end{cases}$

   This leads to $\begin{cases}x=\ .079, & q \text{ and } r \text{ are then}\\ (q+r)=1.921\end{cases}$

   determined by $\begin{cases}q+r=1.921\\ \dfrac{q}{r}=\dfrac{1.760}{.013}\end{cases}$

   which gives $\begin{cases}q=1.91\\ r=\ .01\end{cases}$

The formula is then $Fe\left|\begin{matrix}Fe_{.08}\\ As_{1.91}\\ S_{.01}\end{matrix}\right|$

This has a weight of 203.7 and leads to a density of 7.58.
These values are conveniently gathered together in Table IV.

Table IV. Possible Constants for Löllingite, with Various Possible Disposals of the Excess Iron Atoms

Iron disposal	1. Additional solution	2. Omission solution	3. Proxy solution	4. No excess iron
General formula for löllingite	$Fe\left\|\begin{matrix}As_{2-k}\\ S_k\end{matrix}\right\|+nFe$	$Fe\left\|\begin{matrix}As_{2-s-m}\\ S_s\end{matrix}\right\|$	$Fe\left\|\begin{matrix}Fe_x\\ As_q\\ S_v\end{matrix}\right\|$	$FeAs_2$
Formula for Franklin löllingite	$Fe\left\|\begin{matrix}As_{1.985}\\ S_{.016}\end{matrix}\right\|+.128Fe$	$Fe\left\|\begin{matrix}As_{1.76}\\ S_{.013}\end{matrix}\right\|$	$Fe\left\|\begin{matrix}Fe_{.08}\\ As_{1.91}\\ S_{.01}\end{matrix}\right\|$	
Formula weight for Franklin löllingite	213.3	187.8	203.7	205.8
Density for Franklin löllingite	8.06	6.99	7.58	7.66

The density actually determined by means of a pycnometer was found to be 7.53. This is definitely too low for pure $FeAs_2$, but within about half a per cent of the calculated value on the assumption that iron atoms proxy for arsenic atoms in an otherwise normal crystal structure. This agreement is within the limits of experimental error. This criterion thus not only confirms the accuracy of the chemical analysis, in its apparent arsenic deficiency, but it also definitely proves that the iron excess is to be accounted for through the condition of proxy solid solution.

MARCASITE. In the case of marcasite, the available data are not so precise; they have not all been obtained on marcasite from the same locality, and, finally, the effects to be looked for are less pronounced than in löllingite due to the slighter iron excess in marcasite. Nevertheless, it is possible to arrive at valuable conclusions with the scanty and imperfect data at hand.

Cell constants for marcasite have been published by de Jong[11] Buerger,[12] and Bannister.[13]
These are as follows:

	de Jong	*Buerger*	*Bannister*
a	$\frac{1}{2}\times 3.395$	3.37	3.38Å
b	4.45	4.44	4.44
c	5.42	5.39	5.39
V	81.8	80.6	80.8Å^3

The constants given by Bannister and the writer agree exactly except for the length of the *a* axis. The writer has gone over his original measurements and finds that the length of this axis was determined by averaging the distances of spots appearing in two pairs of layer lines. The average of each pair of layer lines agrees with that of the other within one part on two thousand, so these measurements seem to be trustworthy ones. It will appear in a subsequent publication that the length of the *a* axis shrinks with increasing iron content, without great effect on the other axes, so Bannister's and the writer's data may be considered to be in complete harmony for crystals of slightly different iron content. Since

[11] W. F. de Jong, Bepaling van de absolute aslengten van markasiet et daarmee isomorfe mineralen: *Physica,* **6,** pp. 325–332, 1926.

[12] M. J. Buerger, The Crystal Structure of Marcasite: *Am. Mineral.,* **16,** pp. 361–395, 1931.

[13] F. A. Bannister, The distinction of pyrite from marcasite in nodular growths: *Min. Mag.,* **23,** pp. 179–187, 1932.

a density will be introduced which was measured on the very crystals on which the writer made x-ray determinations, his own value of the cell dimensions will be retained. De Jong's results are so different that it appears likely that he made his measurements on crystals containing other than iron and sulfur in their compositions, probably arsenic.

A critical quantitative analysis is not available for the marcasite used by the writer, but a qualitative analysis has ascertained it to be free from the usual impurities to be expected for this mineral. In lieu of the actual iron:sulfur ratio, therefore, it will probably not be far wrong to assume a value of 1:1.985, which is the average value deduced for marcasite. The constitution of the cell may then be studied according to the general cases discussed above. The resulting constants are given in table V. The density actually determined by pycnometer was 4.92, which agrees only with an excess of iron if it is in the structure as a proxy solid solution, as was

Table V. Possible Constants for Marcasite, with Various Possible Disposals of the Excess Iron Atoms

Iron disposal	1. Addition solution	2. Omission solution	3. Proxy solution	No excess iron
General formula for marcasite	$FeS_2+n Fe$	FeS_{2-m}	$Fe\left\vert\begin{matrix}Fe_x\\S_{2-x}\end{matrix}\right\vert$	FeS_2
Formula for marcasite assuming: $\frac{Fe}{S}=\frac{1}{1.985}$	$FeS_2+.0755\ Fe$	$FeS_{1.985}$	$Fe\left\vert\begin{matrix}Fe_{.004}\\S_{1.996}\end{matrix}\right\vert$	
Formula weight for marcasite assuming: $\frac{Fe}{S}=\frac{1}{1.985}$	124.17	119.45	120.1	119.97
Density of marcasite assuming: $\frac{Fe}{S}=\frac{1}{1.985}$	5.08^{+}	4.88	4.92	4.91

the case with löllingite. While this is not a very sensitive criterion for distinguishing pure FeS_2 from a compound containing excess iron, it should be pointed out that the agreement is better with excess iron than without it, which tends to raise confidence that the excess iron indicated by chemical analyses is real and not due to some sort of systematic analytical error.

It should be noted that if Bannister's dimensions for the marcasite cell be used instead of the writer's, the densities calculated in Table V would each be decreased by about 0.01. If the excess iron which appears in the chemical analyses is conceded to be real, it can only be accounted for as proxying for sulfur atoms, regardless of whose values for the marcasite cell are selected. Furthermore, if the iron:sulfur ratio of marcasite is eventually found to be somewhat different than that deduced in the preceding discussion of analyses, or if it is found to be variable, the value of the density which will be least affected by the change is the density calculated on the basis of proxy solution.

In connection with the original data used for the marcasite given above, it should be pointed out also that these figures were a matter of published record[14] before the theory of excess iron in marcasite had been developed, and that they can therefore be relied upon to be unprejudiced by theoretical views. It is necessary to mention this due to the fact that the writer's published density is in excess of any other published for marcasite including that of Allen, Crenshaw, Johnston, and Larsen's[15] figure of 4.89. It is interesting to note that the density of the material used by these investigators rose to 4.91 after heating to about 620°C. and cooling.

The Pyrite-Marcasite Relation

All evidence points to the fact that pyrite is pure, or very approximately pure, FeS_2, while marcasite is $Fe \left| \begin{matrix} Fe_x \\ S_{2-x} \end{matrix} \right|$, where x is a small fraction in the neighborhood of .004, giving marcasite an empirical composition of $FeS_{1:1.985}$ or thereabouts. It is, therefore, incorrect to speak of pyrite and marcasite as polymorphous forms of the same compound, in the usual sense of the word polymorphous. It follows that one cannot speak of marcasite as un-

[14] Reference 12, pp. 366 and 367.

[15] Reference 1, p. 188.

stable with respect to pyrite, any more than one can speak of pyrrhotite as unstable with respect to pyrite. They are chemically distinct. The relation between pyrite and marcasite is, therefore, primarily a chemical one; fundamentally it may be expressed by the equation:

$$x\mathrm{Fe}+\mathrm{FeS_2}=\mathrm{Fe}\left|\begin{matrix}\mathrm{Fe}_x\\ \mathrm{S}_{2-x}\end{matrix}\right|+x\mathrm{S} \qquad (1)$$

pyrite marcasite

If the iron is added to pyrite in water solution (1) becomes

$$x\ \mathrm{Fe^{++}}+\mathrm{FeS_2}=\mathrm{Fe}\left|\begin{matrix}\mathrm{Fe}_x\\ \mathrm{S}_{2-x}\end{matrix}\right|+x\mathrm{S}+2x\oplus \qquad (2)$$

pyrite marcasite

It is known from the work of Allen, Crenshaw, Johnston, and Larsen that in the presence of acid, the right member of this equation tends to be formed in preference to the left member. This fact may be combined with equation (2) to give the following:

$$2x\mathrm{H^+}+x\mathrm{Fe^{++}}+\mathrm{FeS_2}=\mathrm{Fe}\left|\begin{matrix}\mathrm{Fe}_x\\ \mathrm{S}_{2-x}\end{matrix}\right|+x\mathrm{H_2S}\uparrow+4x\oplus \qquad (3)$$

pyrite marcasite

The positive charge appearing on the right may be expected to be absorbed by any substance present at the time of the reaction which is capable of being oxidized. For example, if ferrous iron is used as sulfate to supply the excess iron required by marcasite, as in the experiments by Allen, Crenshaw and Merwin, the following equation may be expected to hold:

$$x\mathrm{H_2SO_4}+(1+4)x\mathrm{FeSO_4}+\mathrm{FeS_2}=\mathrm{Fe}\left|\begin{matrix}\mathrm{Fe}_x\\ \mathrm{S}_{2-x}\end{matrix}\right|+x\mathrm{H_2S}\uparrow+2x\mathrm{Fe_2(SO_4)_3} \qquad (4)$$

pyrite marcasite

where x formula weights of $\mathrm{FeSO_4}$ go to supply the excess iron for marcasite and $4x$ formula weights are used to absorb the positive charge. In part, however, the liberated sulfate is probably also concerned in absorbing the charge, thus:

$$x\mathrm{H_2SO_4}+x\mathrm{FeSO_4}+\mathrm{FeS_2}=\mathrm{Fe}\left|\begin{matrix}\mathrm{Fe}_x\\ \mathrm{S}_{2-x}\end{matrix}\right|+x\mathrm{H_2S}+\overbrace{2x\mathrm{SO_4}+4x\oplus}^{\underbrace{2\mathrm{SO_2}+2\mathrm{O_2}}_{\rightleftharpoons}} \quad (5)$$

pyrite marcasite

Possible substantiation for this latter reaction is supplied by Allen, Crenshaw, and Merwin, who mention, ". . . sulfur dioxide, which forms when the temperature and acidity are sufficiently high. . ."[16]. These investigators have explained the formation of sulfur dioxide thus (page 396):

"At the higher temperature and the higher acid concentrations a side reaction becomes manifest, viz: the reduction of the sulphuric acid to sulphur by the hydrogen sulphide, followed in turn by the interaction of the sulphur with the sulphuric acid and the appearance of sulphur dioxide."

Equation (5) may be expected to at least add to the sulfur dioxide formation, if it does not actually account for much of it.

It should be pointed out that acid concentration is not the only variable tending to influence the formation of pyrite or marcasite. Equations (3) and (4) indicate that hydrogen ion concentration and iron concentration tend to push the reaction in the direction of forming marcasite, but that this is opposed by the gas pressure of H_2S, which tends to push the reaction towards the formation of pyrite. Equation (3) also indicates that the concentration of the particular agent utilized for absorbing the positive charge freed from the iron will also tend to push the reaction in the direction of marcasite, while the concentration of the resulting oxidized material, unless solid, will tend to reverse this action and to form pyrite.

Needless to say, other acid radicals could be substituted for the sulfate which appears in equations (4) and (5), with similar results, generally speaking.

One may regard the fact that marcasite forms in acid solution as consistent with the fact that marcasite is lower in sulfur than pyrite. The office of the acid is to remove the sulfur from pyrite crystals already formed, or from normal molecular groups of FeS_2 composition about to precipitate, by the action of H^+ upon S to form the removable gas phase H_2S. In the precipitation of FeS_2 by the action of H_2S on a ferrous salt, the products include not only FeS_2 but acid, according to the equation given by Allen,

[16] Reference 2, p. 395.

Crenshaw and Merwin:[17]

$$H_2S + S + FeSO_4 = H_2SO_4 + FeS_2. \tag{6}$$

If the acid formed on the right of equation (6) is not removed from the sphere of influence of the FeS_2 immediately, these can react, in the presence of $FeSO_4$ (which must always be present in the system whether $FeSO_4$ was the original iron sulfate salt used, as in equation (6), or not, because with products H_2SO_4 and FeS_2, equation (6) must always come to equilibrium and $FeSO_4$ must be present by its action from right to left) and form marcasite as indicated by equation (4) and perhaps (5). If, however, some material with an alkaline reaction is present to remove the acid formed by equation (6), only the normal FeS_2 or pyrite is formed.

As a consequence, then, of the low sulfur content of marcasite, as compared with the high sulfur content of pyrite, the formation of pyrite in alkaline solutions and the formation of marcasite in acid solutions receives reasonable explanation. In anticipation, it may be said that a like relation holds between sphalerite (the so-called "stable," but actually the high-sulfur, form of ZnS) and wurtzite (the so-called "unstable," but actually the low-sulfur form of ZnS). The evidence [18] for this, together with the structural significance will appear shortly.

[17] Reference 2, p. 396.

[18] M. J. Buerger, The Sphalerite-Wurtzite Relation, to appear shortly.

THE DETERMINATION OF OPTIC ANGLE WITH THE UNIVERSAL STAGE

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ABSTRACT

With the universal stage direct measurement of the optic angle of a biaxial crystal by rotation from a bisectrix to one or both optic axes is frequently not possible. Berek's graphical method of determination for this case is outlined here and modified to give greater flexibility and usefulness by the addition of a more comprehensive group of curves. These permit the attainment of the maximum accuracy possible under any given set of conditions. The method involves only a few simple rotations on the universal stage and is equally applicable to the old or new models. Used with the modified instrument having two east-west axes, the new curves form an integral part of universal stage procedure involving no graphical construction on the part of the operator and no corrections during experimental procedure.

In the determination of optic angle with the Fedorov Stage they afford a most valuable check whenever the complete angle, 2V, cannot be measured directly.

INTRODUCTION

Berek[1] has developed a procedure for thin-section study of biaxial minerals on the Leitz model universal stage, an essential part of which is the determination of the optic orientation and optic angle. This is performed as follows: After locating the position of the first and second optic symmetry planes, an optic symmetry axis is made vertical with the aid of a stereographic projection by rotation on the north-south horizontal and the inner vertical axes. The crystal is then turned to extinction on the outer vertical axis. From this oriented position in which two of the optic symmetry planes are parallel to the two nicols (*i.e.* north-south and east-west) and an optic symmetry axis is parallel to the axis of the microscope, the crystal is turned 45° on the outer vertical axis (*rotation* $\bar{\varphi}$) to what may be called *the reference position* and then 54.7° on the outer east-west horizontal axis (*rotation* x). Finally, it is turned to extinction on the microscope stage (*rotation* ϕ). For the given value of the angle ϕ a "Normaldiagramm" (Fig. 1) indicates the orientation in the reference position of the optic plane and acute bisectrix, and the approximate size of the optic angle. To determine the latter more accurately different rotation angles $\bar{\varphi}$ and x of size depending upon the orientation of the optic symmetry elements and the value of 2V just obtained are used in conjunction with a particular curve of a "Spezialdiagramm."

[1] M. Berek, Neue Wege zur Universalmethode: *Neues Jahrb. f. Min., Geol., und Pal., Beilage Band*, **1923.**

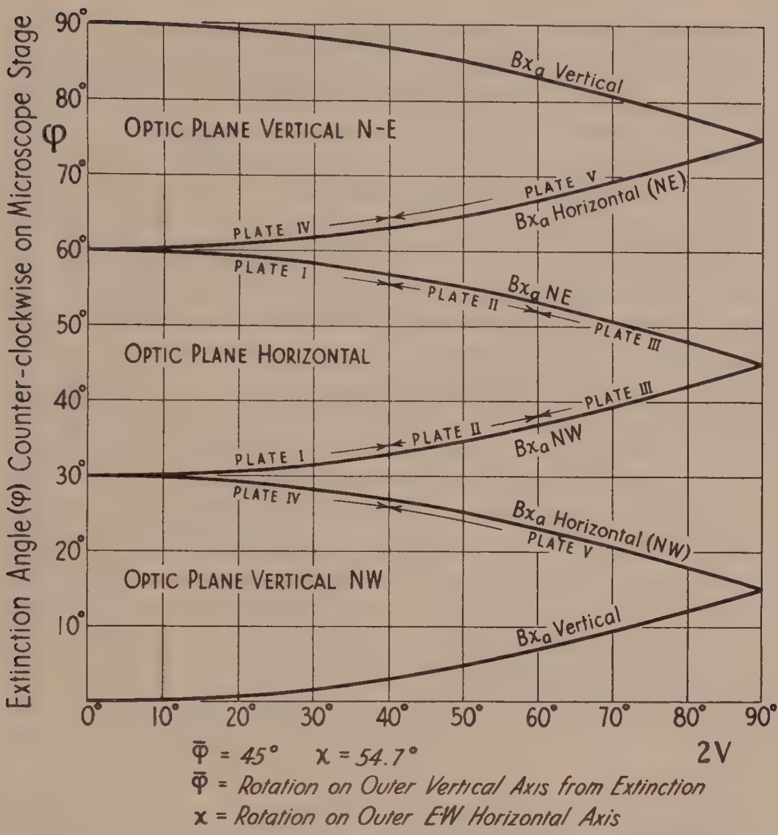

FIG. 1. Graph for determination of optic orientation in the reference position and of approximate size of 2V. Rotations $\bar{\varphi}$, x, and ϕ are made in this order. It is used prior to determination of optic sign and accurate determination of optic angle with plate indicated.

It is to this last named step that attention is called here. For a particular value of 2V and a given orientation there is one curve which will give maximum accuracy. It is represented by rotations $\bar{\varphi}$ and x of definite size. For any other value of the optic angle this will not be the most accurate curve. Theoretically, therefore, it would be desirable to have a different curve for every value of 2V, assuming a given orientation. Practically, of course, this is out of the question, and also the curve of maximum accuracy often involves so large a rotation x as to be impractical from a mechanical and optical standpoint. Berek has chosen, therefore, three ranges

of 2V, and for each of these he has constructed three curves for the three possible orientations. The accuracy of each curve is as great as can be obtained with a rotation value of x which under normal conditions can always be made.

There are three limitations, however, attendant upon so restricted a choice. First, it is often possible in thin-section work to make a rotation x larger than that demanded by a given curve of Berek's "Spezialdiagramm." Now in general, accuracy increases with increase in x up to large values, so that it is frequently the case that a more accurate result than is possible with the "Spezialdiagramm" could be obtained were a suitable curve available. Secondly, in immersion work the converse is true. Thus it is often not possible to rotate through the angle x necessary for the given curve. In such an event one is limited to the approximate result of the "Normaldiagramm." With a curve for the maximum obtainable value of x under these conditions, a more accurate result would be obtained. Thirdly, with the "Spezialdiagramm" the value of x must be corrected for the difference in index between the hemisphere and mineral before the rotation is made. The index of the mineral, however, is not ordinarily obtained until after determining the optic orientation while the determination of 2V is most conveniently made at the same time as that of the orientation. It would be more logical, therefore, for the determination of optic angle to precede index determination rather than to follow it.

The purpose here is to present a procedure and accompanying curves intended to minimize these limitations on convenience and accuracy. Five groups of curves have been plotted, of which three apply to the orientation in which the optic plane is horizontal, and two, to that in which the optic plane is vertical and acute bisectrix horizontal. For the third possible orientation with acute bisectrix vertical 2V is measured by direct reading, and no curves have been calculated. In each of the five groups $\bar{\varphi}$ has a fixed value while x varies in two degree steps from 54° to 82°, approximately. In this way all three of the above mentioned limitations to the "Spezialdiagramm" are at once removed since these two values of x are the practical limits of the range of rotation possible on the outer east-west axis, and the individual curves are close enough together to allow interpolation. Thus the result of an optic angle determination is not restricted to the accuracy obtainable with

the "Normaldiagramm" or "Spezialdiagramm," and no corrections are needed during experimental work. Furthermore, since the relative care with which different parts of universal stage procedure are carried out and differences in optical properties of various minerals influence the relative accuracy of different curves of any one of the five groups, individual differences in minerals and in experimental work can be compensated by correct choice of curves.

Since the introduction of the modified instrument having two east-west axes universal stage procedure has become much more simple and rapid. The present method of optic angle determination is designed to conform to these recent improvements, to increase the accuracy of 2V determinations, and to make them possible under all conditions of experimental work. Its field of application is not limited, however, to the modified instrument. With the Leitz model (Fedorov) stage this method of optic angle determination forms a supplementary procedure of use whenever an optic axis cannot be brought into the field of view, and it affords a most valuable check whenever the complete angle, 2V, cannot be measured directly.

The author wishes to express acknowledgement to Professor R. C. Emmons for suggesting the problem and giving the greatest help in its pursual.

Procedure

The procedure recommended for use with the curves accompanying this paper is similar to that outlined above, but for those not familiar with Berek's method the following detailed description will be of use. There are two principal steps: first, the determination with the aid of Fig. 1. of the orientation of the optic elements of the crystal in the reference position and the approximate size of the optic angle, and, second, the accurate determination of the optic angle by direct reading or by use of Plates I–V.

The first step consists of the three rotations: $\bar{\varphi}=45°$, $x=54.7°$, and ϕ. Rotation $\bar{\phi}$ is made in either direction on the outer vertical axis from the oriented position in which an optic symmetry axis is parallel to the microscope and two optic symmetry planes are north-south and east-west. After this rotation of forty-five degrees the crystal is in *the reference position*. Rotation x is made in either direction on the outer east-west horizontal axis. The rotation angle of 54.7° is crystallographic, so that the actual rotation will be less

I OPTIC PLANE HORIZONTAL; 2V, 0°-40°

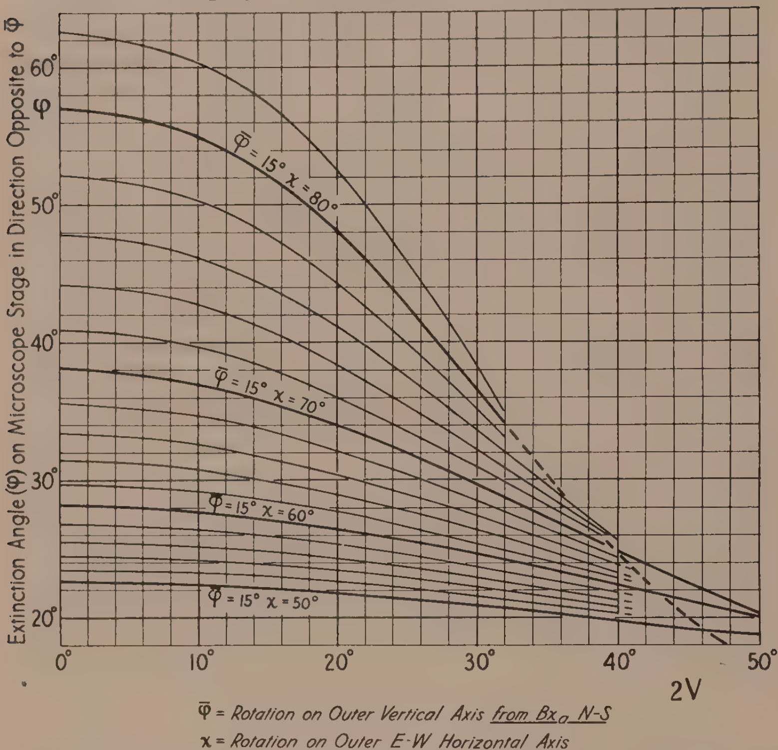

PLATE I. Graph for the determination of 2V. Rotations $\bar{\varphi}$, x, and ϕ are made in this order. Make rotation x as large as possible up to 82°. Do not interpolate between curves for x greater than 70° beyond where these curves end. If exact rotation $x=80°$ is made, the dotted portion of this curve may be used. For 2V less than 15° the curves give inaccurate results.

or more than this value depending upon whether the index of the hemisphere is smaller or greater than that of the mineral, but the correction can usually be estimated with sufficient accuracy for this procedure since ordinarily the approximate index of the mineral is known. Lastly, rotation ϕ is made counter-clockwise to extinction on the microscope stage.

Using this value of ϕ as ordinate, a point on one of the six curves of Fig. 1. is located. This gives the orientation of the optic plane and acute bisectrix in the reference position and the approximate size of the optic angle. It also indicates the plate to be used in the more accurate determination of 2V.

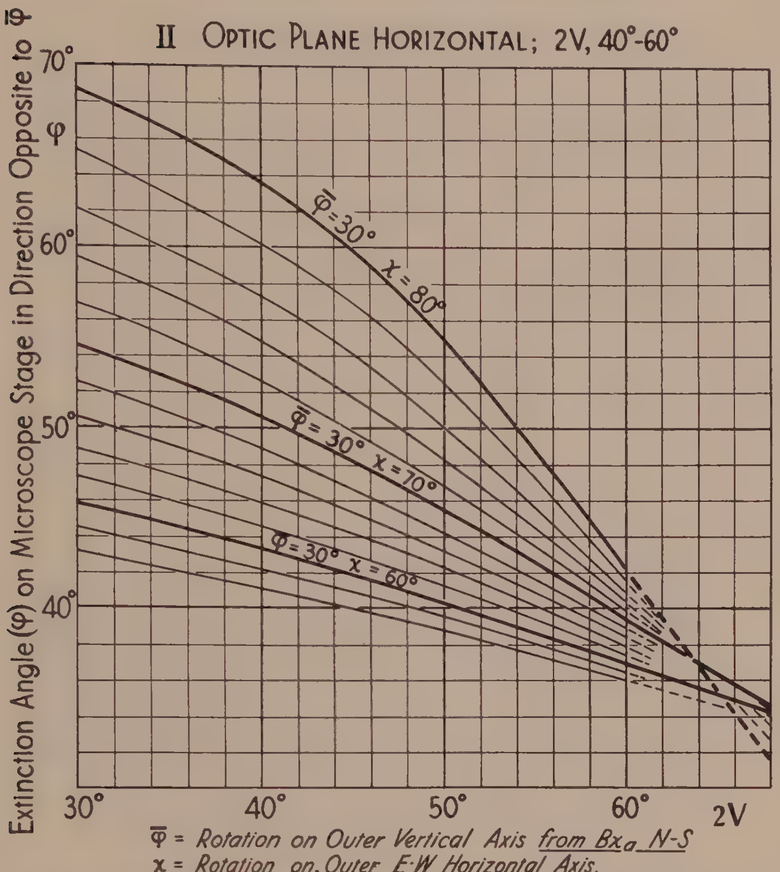

PLATE II. Graph for the determination of 2V. Rotations $\bar{\varphi}$, x, and ϕ are made in this order. Make rotation x as large as possible up to 80°. For 2V greater than 64° the curves from $x=70°$ to $x=80°$ are reversed.

It is well to notice that the extinction angle ϕ must be read carefully. If the value of ϕ is near the borderline between two different optic orientations, the following precautions are necessary. If ϕ is near 15° or 75°, in order to be sure whether the acute bisectrix is vertical or horizontal, direct reading should be made as described below. If ϕ is near 45°, in order to determine whether the acute bisectrix is northwest or northeast, rotation x on the outer east-west axis should be made as great as possible. An extinction value ϕ greater than 45° will prove that Bx_a is northeast,

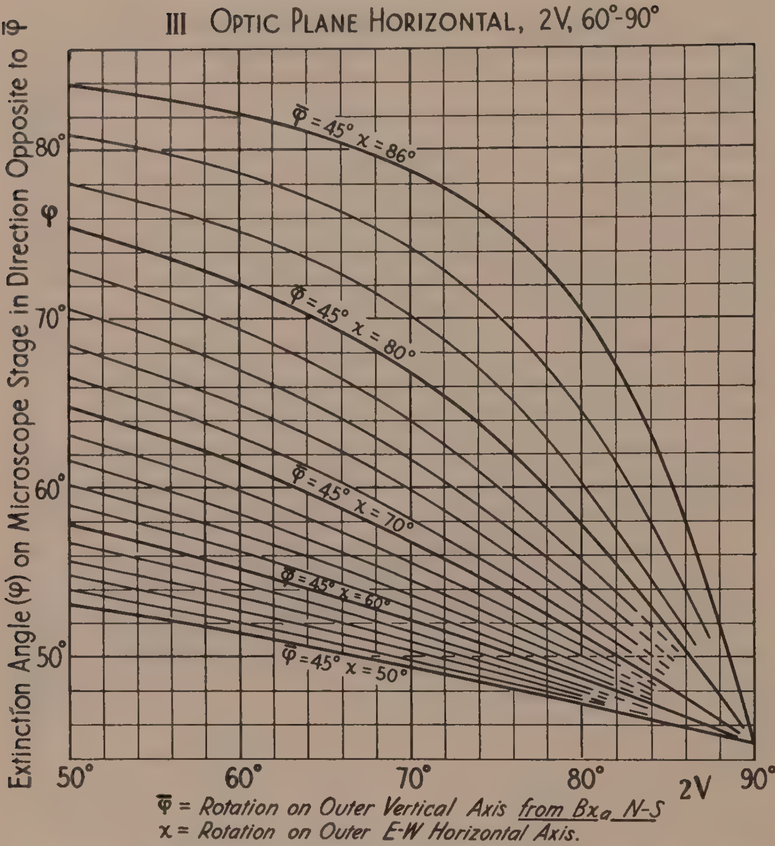

PLATE III. Graph for the determination of 2V. Rotations $\bar{\varphi}$, x, and ϕ are made in this order. In ordinary work make rotation x as large as possible up to 74°. If crystal is very carefully oriented and extinction is sharp, make rotation x as large as possible up to 86°.

and one less than 45°, that it is northwest. Unless these precautions are followed in these special cases, a wrong determination of sign may result, and in the first instance, a wrong determination of 2V. If ϕ is near 30° or 60°, there is no precautionary measure other than great care exercised in the performance of the regular procedure.

Before proceeding to the second step the optic sign is determined in the reference position, in which the orientation of the optic plane and acute bisectrix is known. The outer east-west axis

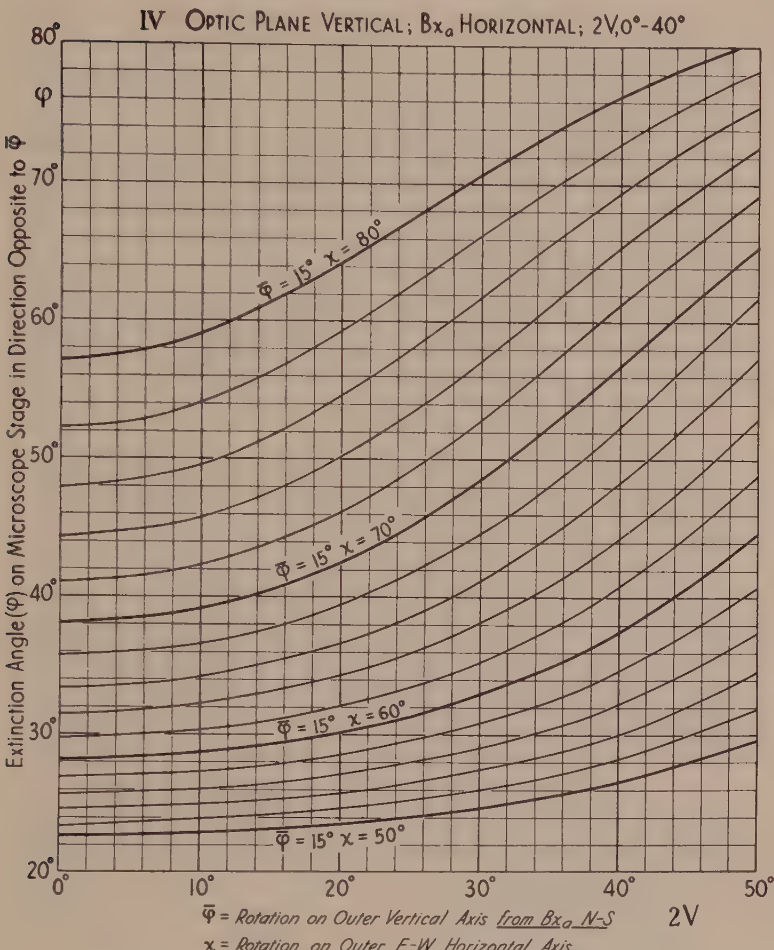

PLATE IV. Graph for the determination of 2V. Rotations $\overline{\varphi}$, x, and ϕ are made in this order. For 2V less than 30° make rotation x as large as possible up to 78°. For 2V greater than 30° make rotation x as large as possible up to 70°. For 2V less than 15° the curves give inaccurate results.

and the microscope stage are returned to the zero reading, and an accessory plate is used. If there is any doubt concerning the result obtained from Fig. 1, the precautionary measures above described should be taken before determining the sign of the mineral.

After the determination of sign *the acute bisectrix or optic plane*

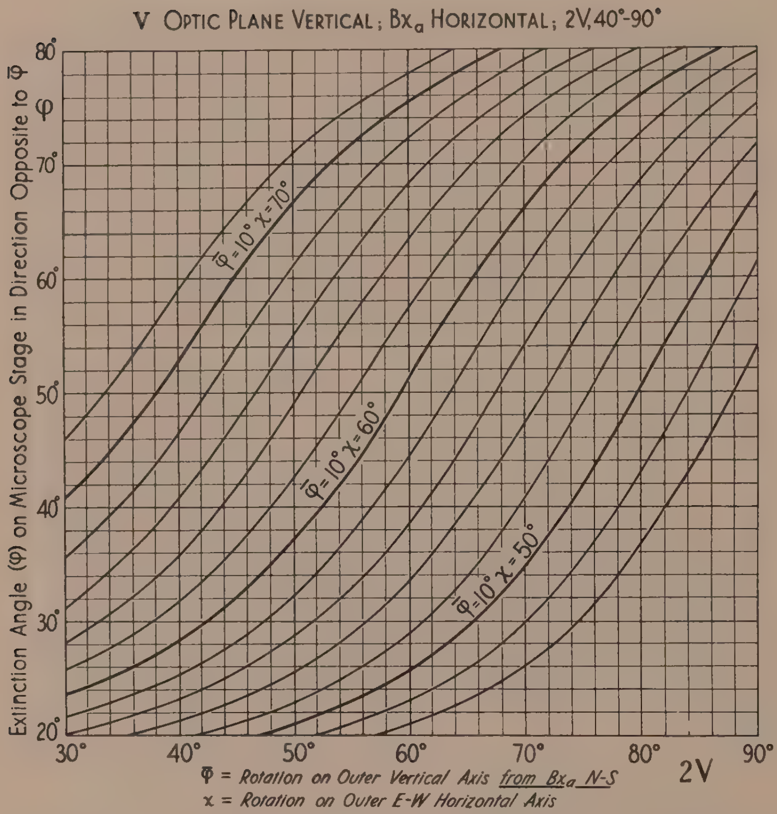

PLATE V. Graph for the determination of 2V. Rotations $\bar{\varphi}$, x, and ϕ are made in this order. The following rotations of x should be made for the various ranges of 2V.

2V=80°–90°, x=48°; 2V=50°–60°, x=62°;
2V=70°–80°, x=52°; 2V=40°–50°, x=68°;
2V=60°–70°, x=58°;

is made north-south by suitable rotation on the outer vertical axis. If, in step one, the acute bisectrix was found to be vertical, or horizontal provided 2V is large, the optic angle can be read directly by turning to the forty-five degree position on the microscope stage and measuring the angle between extinction positions reached by rotation from zero in one or both directions on the outer east-west axis.

If the direct reading is impossible, which will be the case when the optic plane is horizontal, or when it is vertical provided Bx_a

is horizontal and 2V is small, the particular plate indicated by Fig. 1 is used for the accurate determination of 2V. As in step one there are three rotations: $\overline{\varphi}$ on the outer vertical axis *from the north-south position*, x on the outer east-west axis, and ϕ to extinction on the microscope stage *in the direction opposite to* $\overline{\varphi}$. The values of $\overline{\varphi}$ and x to be used are given in the directions accompanying each plate. The extinction angle ϕ must be measured carefully, and it is well to average readings over 360°. With the given value of ϕ as ordinate a point is obtained on the curve corresponding to the value of x corrected for hemisphere index. Ordinarily it will not coincide with any of the curves given, but its position is readily found by interpolation. The size of the optic angle is the abscissa value of the point.

Example

The procedure used in the determination of 2V in a particular topaz section will serve as a specific example and will indicate the order of accuracy commonly obtainable. A crystal of topaz was cut parallel to the base, which is normal to the acute bisectrix, and the optic angle accurately determined as 66° by means of a Fuess rotation apparatus. A section of the same crystal cut parallel of a prism face was oriented on the universal stage and turned to the reference position, that is $\overline{\varphi}=45°$. Knowing the index of topaz to be a little less than that of the hemisphere (1.649), a rotation x of 54° (instead of 54.7°) was made on the outer east-west axis. The crystal was then turned counterclockwise to extinction through an angle of 22°. With this value it is found on Fig. 1 that the optic plane is vertical and the acute bisectrix horizontal and northwest in the reference position, that 2V is approximately 65°, and that Plate V should be used for the second step. Returning to the reference position by rotation to the zero readings on the outer east-west axis and the microscope stage, the sign of the mineral was determined by insertion of the gypsum plate with slow ray northwest. A rise in color showed the mineral to be positive since the acute bisectrix was northwest.

By a rotation of forty-five degrees clockwise on the outer vertical axis, the optic plane and acute bisectrix became north-south. Referring to Plate V it is found that for an optic angle of about 65° rotations $\overline{\varphi}=10°$ and $x=58°$ should be made. The crystal was turned, therefore, ten degrees (*counter-clockwise*) on the outer

vertical axis and fifty-eight degrees (south) on the outer east-west axis. A value for ϕ of 58° was obtained by rotating *clockwise* to extinction on the microscope stage. Before using Plate V the value $x=58°$ must be corrected. This is done by use of a Fedorov net[2] here represented by Fig. 2. Point *a* is the location of the normal to the inner stage in the oriented position (inner east-west axis 3.5°N; north-south axis 22°E.). Point *b* is its location after the rotation $\bar{\varphi}=10°$. Point *c* is its location after rotating *x* fifty-eight degrees south. The path followed is an arc convex toward the center

FIG. 2. Key to the use of the Fedorov net in correcting value of rotation *x*.

of the figure and the 58° is measured on the arcs of the great circles intersecting this path. Point *b* is seen to be 22° (as measured on the circles in the plane of the diagram) from the center along a radial, and point *c*, 57°. These two values are corrected for difference in index between the hemisphere and mineral by means of von Fedorov's diagram.[3] The index of the hemisphere is 1.649. The index to use for the mineral will be different in the two cases.

[2] Albert Johannsen, *Manual of Petrographic Methods*, pages 15 and 17, sec. ed., McGraw-Hill Book Co., **1918**.

[3] R. C. Emmons, A Modified Universal Stage: *Am. Mineral.*, Vol. **14**, pp. 441–461, 1929.

For point *b* the high index (1.625) is used because for that position of the normal to the inner stage Z is approximately north-south and horizontal. For point *c* the mean index (1.618) is used because in that position an optic axis is not far from vertical. Thus the values 22.5° and 58.5° are obtained for points b' and c', respectively. Measuring now the angle between b' and c', the true value, $x=60°$, is obtained (In Fig. 2 the distance $b'c'$ is greatly exaggerated).

With 58° as ordinate a point on the curve $x=60°$ gives a value of 64° for the optic angle. Other determinations varied an equal amount on either side of the correct value of 66°.

Accuracy

Any analysis of the accuracy of this method of determining 2V, aside from empirical observation, is complicated by the variability of different minerals as regards sharpness of extinction in different directions. However, this factor can to a certain extent be taken into consideration, and a reasonably good estimate of accuracy can be made without regard to it. Such an estimate is indispensable to an intelligent use of the procedure.

Estimation of the effect of sharpness of extinction upon accuracy can at best be only qualitative but is of some use. Thus, if the extinction angle ϕ is determined for an orientation in which an optic axis is nearly vertical, the result will not be as accurate as if ϕ were determined for an orientation with the optic plane nearly horizontal. In curves where errors in ϕ produce large errors in 2V, the orientation of the optic plane and the optic axes with reference to the axis of the microscope will have, therefore, great effect upon the accuracy of the determination of 2V.

From an examination of the curves themselves two important sources of error are apparent: inaccurate determination of ϕ, and inaccurate rotation x. With reference to the first of these it is apparent that for a curve making an angle of forty-five degrees with the 2V axis an error of one degree in ϕ results in an error of one degree in 2V. If this angle is greater or less than forty-five degrees, the corresponding error in 2V will be less or greater than unity. As to the second source of error, inaccuracies in x may arise from imperfect orientation of the crystal. To illustrate, if the east-west optic symmetry plane were tilted one degree north or south in the oriented position instead of being vertical, there would be

an error in rotation x of almost one degree if rotation $\bar{\varphi}$ were small. Where the curves of Plates I–V are far apart along lines parallel to the 2V axis, small error in x gives a large error in determining 2V.

It is necessary, therefore, in using this procedure to keep in mind these three factors: sharpness of extinction, relation of error in ϕ to error in 2V, and relation of error in x to error in 2V. An example will serve best to clarify this point. If Fig. 1 indicates that the optic plane is horizontal and 2V is about 80°, Plate III is used with a value for $\bar{\varphi}$ of 45° while x may have any value from 50° to 86°. Obviously 50° is a poor choice since an error in ϕ of one degree gives an error in 2V of four degrees. For the curve $x=86°$ a one degree error in ϕ gives a half a degree error in 2V. However, there are the two other factors to consider. First, for $x=86°$ and $2V=80°$, an optic axis is very nearly vertical, so that it will be difficult to determine ϕ accurately. More important is the fact that an error in x of one degree gives an error in 2V of two degrees. Unless, therefore, the orientation of the crystal is very good and the extinction is very sharp, less accuracy will be obtained by a rotation of 86° than by one of 74° where an error in x of two degrees gives an error in 2V of one degree, and where an optic axis is less nearly vertical, even though an error of one degree in ϕ gives an error in 2V of one and one-half degrees. The relative importance of these factors in the choice of x is not easy to determine and varies with different minerals and different workers, but a general comprehension of their significance greatly enhances the accuracy of a 2V determination by this procedure.

The actual accuracy usually obtained varies principally with the size of the optic angle. In general the larger the value of 2V, the greater the accuracy. For an optic angle less than twenty degrees an error of ten degrees is not excessive. For values of 2V above twenty degrees careful work yields results within two to three degrees and occasionally within one degree.

By direct reading an error less than two degrees is usually possible. Berek's "Spezialdiagramm" contains curves for the orientation in which the acute bisectrix is vertical, but for this case direct reading is considerably more accurate, and no such curves are presented here. However, if only the half angle, V, can be measured directly as is ordinarily the case with the standard Fedorov instrument, it is doubtful whether direct reading is as accurate as indirect except when the acute bisectrix is vertical.

The loci of the curves themselves are more accurate than experimental determinations require. Points have been plotted every four to ten degrees, and errors in single points are not important.

Derivation of the Curves

The above outlined method for the graphical determination of 2V is based upon the fact, derived from trigonometric relationships and the Biot-Fresnel rule of crystal optics, that for a given random position of the optic plane of a biaxial crystal the size of the extinction angle in a given direction is a function of the size of the optic angle. If this random position of the crystal is known, it is possible, therefore, to determine the optic angle from the extinction angle about a given axis. With the universal stage where rotations are made upon axes lying in planes of optic symmetry, the problem of obtaining an expression for this relationship is greatly simplified.

Thus for the case in which the optic plane is horizontal, the relation between ϕ and 2V is the following:

$$\phi = \frac{K+K'}{2}$$

where

$$\tan K = \tan\,(\bar{\varphi}+V)\cos x$$
$$\tan K' = \tan\,(\bar{\varphi}-V)\cos x$$

These equations were used in plotting the curves of Fig. 1 and Plates I–III.

For vertical optic plane (Plates IV &V) the following equation employed by Berek was used.

$$\sec V = \sqrt{\sin^2\bar{\varphi} + \frac{\cos 2\bar{\varphi}}{\sin^2 x} - \frac{\cos x}{\sin^2 x}\sin 2\bar{\phi}\,\mathrm{cotg}\,2\phi}$$

The choice of curves was made with a view to combining accuracy and simplicity. It was based mainly upon graphical trials and the curves used by Berek.

ZOISITE AND OTHER MINERALS INCLUDED IN MICA FROM SPRUCE PINE, NORTH CAROLINA

GEORGE M. HALL, *University of Tennessee.*

Spruce Pine, North Carolina, is the center of a region containing a large number of pegmatite dikes which cut the old crystalline rocks. They range in size from small stringers to huge dikes several hundred feet in width and several miles or more in length. The most abundant minerals in these dikes are feldspar, mica and quartz. The district is an important feldspar producing center. In places the feldspar is altered to kaolin, and large quantities of kaolin are mined, washed and shipped to potteries and other users.

The material upon which this paper is based was collected during the early part of April, 1931, by H. C. Amick, a colleague at the University of Tennessee and the writer, in company with Mr. J. C. Pittman, owner of the Chestnut Flat Mine. The mine consists of a number of openings on the hillside high above the creek valley, and is operated for feldspar, which is chiefly microcline, the only sodic feldspar present occurring as perthitic lenses in it, but the dike contains quartz, mica, garnets, pitchblende and other minerals. Pure feldspar is desired and the other minerals are carefully sorted out. The amount of pitchblende is very small. Locally associated with the pitchblende are hydrated uranium minerals of brilliant shades of red, yellow, and green. The mica, muscovite, occurs in "books" or masses of different sizes. They vary from 1 to 30 inches in diameter and from two or three inches to 15 or 20 inches in thickness. The mica masses occur sparingly in most places, but locally they become more numerous. In general, the mica is not first grade and most of it is of such poor quality that it must be rejected and thrown on the dump. By careful sorting and trimming some saleable mica can be obtained. The major portion of the mica is reported to be sold to the electrical trade. Associated with the muscovite are several minerals, biotite, in small amounts; garnet; magnetite; branching groups of zoisite crystals; quartz; and small tufts of crystals that are probably zoisite. While the occurrence of minerals as inclusions in mica is well known, it is believed that the occurrence of zoisite in muscovite is new, as is also garnets with inclusions.

Zoisite ordinarily occurs in masses of small threads and needles as a product of metamorphism. However, large, coarsely crystalline

masses of this mineral were once obtained at Ducktown, Tennessee. At the Chestnut Flat Mine in April, 1931, a mineral was discovered which was new to the workmen. Superficially, it resembled enstatite or tremolite, but later optical examination showed it to be zoisite. It occurs in extremely flat elongated crystals which radiate from common centers. Moreover, the needles from

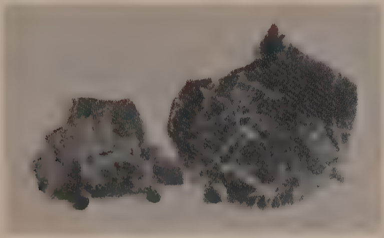

FIG. 1. Zoisite on cleavage plates of mica.

adjacent centers intersect, yielding patterns like that shown in fig. 1. The crystals in these specimens are more than 50 cm. in length, but in others they are much smaller. In some cases the growth of the needles seems to have been entirely between the "leaves" or cleavage plates of the "books" of mica while in other instances, as in fig. 1, the crystals are several millimeters thick,

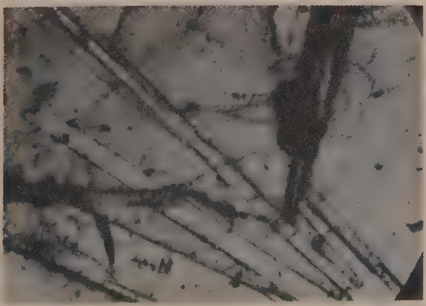

FIG. 2. Fine needles of zoisite in muscovite. Magnification 13×.

and the casts of the crystals with the impression of the striations are conspicuous when the zoisite crystals are removed from the mica host. The cleavage sheets of muscovite frequently have grooves, caused by impressions of the included crystals in them, when torn from the mass. The fine needles of zoisite are shown in fig. 2 as they appear under the microscope. Another type of

zoisite forms fibrous, spherical masses which have a decided tendency to grow by penetrating through the mica rather than by developing along the cleavage planes. This type appears to have formed during the crystallization of the muscovite, as is shown in fig. 3.

FIG. 3. Fibrous, spherical masses of zoisite penetrating muscovite. Magnification 30×.

Associated with the muscovite is some biotite. Hand specimens of the latter mineral can be obtained from the waste dump. Under the microscope, the biotite occurs in small, extremely thin crystals in the muscovite. Due to their dark color they photograph black under the microscope. Other small lens-like masses of similar size and shape are opaque and prove to be magnetite. These magnetite masses are cracked, as shown in fig. 4, in a manner resembling

Fig. 4. Cracked magnetite in muscovite. Magnification 13×.

the pattern of a basal section of columnar basalt. It suggests that the biotite was altered and the iron oxide portion of the mineral

was changed to magnetite but that the area was too great to permit the formation of a continuous film, or that the film was continuous originally but broke up in cooling in order to afford relief from strain.

Hematite occurs in minute scales which are blood red in transmitted light.

The garnets included in the muscovite from this locality are well known. They are chiefly rhombic dodecahedrons and trapezohedrons with two parallel and relatively large faces and the others greatly reduced in size. The garnets resemble the variety pyrope, but contain sufficient amounts of iron and calcium to give definite reactions for these elements. Garnets richer in iron and calcium occur in the pegmatite in association with microcline feldspar. The garnets associated with feldspar are much larger and the faces are approximately equally developed. However, they are so well attached that it is difficult, if not impossible, to obtain crystals free from feldspar. The feldspar and garnet weather with almost equal rapidity and good crystals cannot be obtained from the weathered masses. The garnets in the muscovite are shown in fig. 5. The largest of these garnets is less than a centimeter in

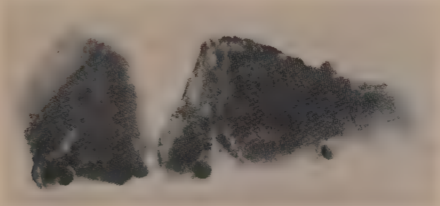

FIG. 5. Flattened garnets in muscovite.

diameter. On account of the size of some of the garnets workmen often examine the garnetiferous books of mica, before they are thrown on the waste heap, for garnets sufficiently large for cutting, but they report that they find few suitable for this purpose. The garnet shown in fig. 6 is a relatively clear one, but it shows a distinct zonal structure as shown by variations in both color and birefringence. The black specks are magnetite grains that show prominently in the mica and lie either above or below the garnet. Fig. 7

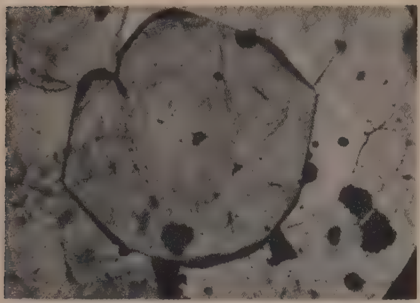

FIG. 6. Flattened garnet showing zonal structure. Magnification 13×.

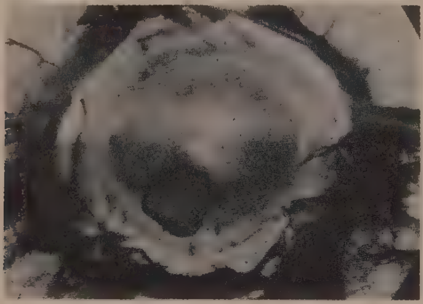

FIG. 7. Garnet included in a garnet in muscovite. Magnification 13×.

shows a garnet with another garnet included within it. The included garnet appears to be oriented approximately 180 degrees with reference to its host.

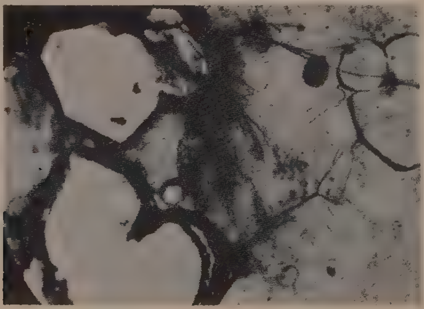

FIG. 8. Flattened quartz and garnet in muscovite. Magnification 13×.

The quartz crystals shown in fig. 8 are distinctly flattened. The difference in indices of refraction of garnet, muscovite and quartz are clearly shown in this figure.

ALLANITE FROM WYOMING*

R. C. Wells, *U. S. Geological Survey.*

Although some 40 analyses of allanite are given in Dana *System of Mineralogy* not one of them shows the presence of any lead whatever. Thorium was determined in seventeen of them. The object of the present note is merely to place on record the results of an analysis of allanite by the writer in which efforts were made to determine thorium, uranium, and lead. These were all found although the percentage of uranium was very small. Work with the rare earths was largely confined to the separation of thorium and cerium from the others. From the few tests made the remaining rare earths were thought to be mainly lanthanum and didymium, that is, the other members of the cerium group.

Analysis

SiO_2	33.64	
ThO_2	1.28	=1.12 Th
TiO_2	0.24	
Al_2O_3	12.16	
Fe_2O_3	7.67	
Ce_2O_3	14.63	
$(La, Di)_2O_3$	7.34	
FeO	8.46	
MnO	0.25	
CaO	9.75	
MgO	1.83	
H_2O	2.84	
U_3O_8	0.02	=.017 U
PbO	0.11	=.102 Pb
BeO	None	
	100.22	

Sp. Gr. = 3.72

Age by logarithmic formula = 1500 million years.

The age is calculated on the assumption that all of the lead is of radioactive origin. This may not be valid but the analysis is of interest as at least showing the presence of thorium, uranium, and lead.

This allanite was submitted for identification by F. W. Horton, of the U. S. Bureau of Mines. He received it from Charles Evans of Custer, South Dakota, who collected it from a pegmatite fourteen miles northwest of Wheatland, Wyoming. According to Frank

* Published by permission of the Director of the U. S. Geological Survey.

L. Hess, of the Bureau of Mines, this pegmatite was worked for a time by Herman Reinhold, who claimed that he obtained gadolinite from the pegmatite in considerable quantity. The analysis shows that the mineral is not gadolinite but allanite. A careful test for beryllium was kindly made by J. J. Fahey, but none was found, thus proving the complete absence of gadolinite.

The pieces examined were of irregular shape with resinous luster and black color except for reddish-brown and pale yellow coatings or stains in a few places between the mineral and adjoining rock. Streak, pale gray.

A RECENT FIND OF BIXBYITE AND ASSOCIATED MINERALS IN THE THOMAS RANGE, UTAH

Arthur Montgomery, *New York City.*

Introduction

During early September of 1933 the writer was able to spend a week exploring the northern part of the Thomas Range in west-central Utah. The chief purpose of the trip was to locate if possible the old bixbyite locality where all the best specimens of that mineral have apparently originated. The exact location has never been very clear. It has been described as thirty-five miles south-west of Simpson,[1] and in the southern end of the Dugway Range.[2] Confusion has always arisen from the fact that "Dugway" is a term used locally to include two mountain ranges. The topographic map shows the Thomas and northerly-bordering Dugway Ranges as separated by the Dugway Road which cuts between them from east to west at a point approximately seventeen miles north of Topaz Mountain. It is possible that there may be an occurrence of bixbyite in the southern Dugway Range, but the writer believes that he has found the original locality in the north-east section of the Thomas Range. A day's exploration north of the Dugway Road failed to reveal anything of mineralogical interest.

Locality and Occurrence

In its northern area the Thomas Range widens considerably to the east and west. Numerous ridges extend outward from the central body of the range and, together with their adjoining canyons,

[1] Penfield, S. L., and Foote, H. W., *Am. J. Sci.*, Vol. **4**, pp. 105–110, 1897.

[2] Bixby, Maynard, A Catalogue of Utah Minerals and Localities **1916**, p. 6.

form a veritable maze of hilly topography. The character of this region is the most barren imaginable, with very scant vegetation and no signs of water.

It was in the north-east portion of this area, perhaps three or four miles south of the Dugway Road, that several very interesting mineral occurrences were discovered. At one locality excellent specimens of bixbyite were found, and the writer has reason to believe that this coincides with the original locality of the late Maynard Bixby.

The occurrence of the bixbyite is limited to the southeastern extremity of a ridge which runs in a general north-south direction. This ridge is about 150 feet high and on its eastern slope shows an extensive exposure of the typical whitish-gray rhyolite. The bixbyite is confined further to the lower 20 or 30 feet of the ridge exposure. Associated minerals are topaz, garnet, beryl, hematite, and quartz.

Description of Minerals

Bixbyite

The bixbyite occurs as black crystals on topaz, on garnet, and in the rhyolite. Those of the former occurrence are usually larger than the others and more numerous. The bixbyite crystals tend to form in clusters near one end of a topaz crystal or else are found scattered along the prism. That the formation of the bixbyite followed very closely, indeed coincidently, with that of the topaz is indicated by the fact that the topaz often has been forced to make room for the later-forming mineral.

Bixbyite crystals on garnet occur indiscriminately; are generally quite small but numerous. Those in rhyolite occur in small cavities of the rock and are neither so large nor numerous as in either of the other occurrences.

Practically all the crystals are simple cubes with the exception of those which occur in a small area on the southerly tip of the ridge. Here the typical crystal is the cube modified by the tetragonal trisoctahedron $n(211)$. These crystals, associated with rough, opaque topaz, are very numerous but never larger than 3 or 4 mm. in diameter. One group of modified crystals was found to have the octahedron $o(111)$ present in addition to $n(211)$. So far as the writer has been able to learn, this is a new form for bixbyite.

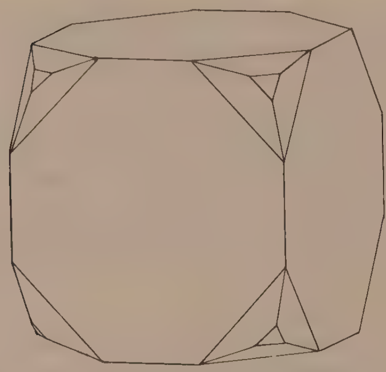

FIG. 1. Crystal of bixbyite with $a(100)$, $n(211)$, and $o(111)$.

Examples of interpenetration twinning on (111), as in fluorite, were found to be not unusual. Some of the bixbyite crystals proved to be quite large. Four or five individuals measured a full quarter-inch in diameter, and there are many more cubes of nearly equal size.

TOPAZ

Crystals of topaz are predominately of the gray, opaque type with rough and irregular surfaces. However, parts of these crystals are frequently transparent with crystal faces perfectly developed. This gradation of the opaque to the transparent in topaz is a striking feature of many crystals and clearly shows the opaque character as due to countless included quartz crystals of microscopic size. Individual quartz crystals of this type often can be distinguished with a lens in transparent portions of some topaz.

A few opaque crystals were found with smooth faces. One or two are perfectly developed and doubly terminated. A similar type of crystal has already been described from Topaz Mountain,[3] so that further description of these is unnecessary except for the fact that basal pinacoid (001) and brachydome (021) are both represented in addition to the simple form of prisms and pyramid. Although most of these crystals were picked up loose, it was evident that they had weathered out of near-by masses of a fine-grained rhyolitic tuff. This coincides with Patton's description of the Topaz Mountain occurrence.[4]

[3] Patton, H. B., *Bull. Geol. Soc. Am.*, Vol. **19**, pp. 177–192 1908.

[4] Patton, H. B., *loc. cit.*

Fig. 2. Bixbyite crystal on smooth, opaque topaz.

Some of the crystals of opaque topaz attain considerable size. Crystals nearly two inches in length are not uncommon from this locality, and one or two measured well over two inches. The transparent crystals are generally small, but several were discovered here which may surpass in size any of like type yet found in the Thomas Range. One crystal, an inch in length, measures one-third by one-half inch across the *a* and *b* axes respectively. It is nearly flawless.

Many transparent crystals show a dull coating on certain terminal faces, which appears to be due to etching. It is remarkable that with some faces dulled in this way, other adjoining faces, apparently equally exposed, fail to show any etching effects whatsoever. Some topaz, opaque and transparent, tends towards a dark color. This seems to be due to the presence of included plates of hematite.

Garnet

Garnet, which is plentiful here in cavities of the rhyolite, usually takes the form of rounded, partially-disintegrated crystal fragments. It is rarely that a complete crystal of trapezohedral form is found. Crystals and crystal fragments alike are apt to be coated with a sprinkling of bixbyite.

The composition of this garnet, as determined by Penfield and Foote,[5] seems to be an alteration now constituting a mixture of bixbyite, topaz, and quartz. Before alteration the composition was probably that of spessartite.

The size of the garnets varies from an eighth of an inch to a full inch in diameter. The color is a dark gray. Some of the crystals are found implanted on topaz, indicating a later genesis.

[5] Penfield, S. L., and Foote, H. W., *loc. cit.*

Topaz-Garnet Epigrowth

The surfaces of a few garnets were found partially covered with very small, transparent topaz crystals. The latter, evidently of later origin than other topaz of this locality, form typically a closely-woven, reticulated network of crystals. On closer examination these crystals are seen to be definitely oriented on the garnet.

This same epigrowth of topaz on garnet, probably of identical locality, has been described by Cahn[6] and by Goldschmidt and Schröder.[7] It was found that the crystal forms of the decomposed garnet could be reconstructed by measuring the crystallographic relations of the topaz. The general interpretation was that the topaz crystals had formed practically simultaneously with the garnet, and in orientation with each garnet crystal. Later the garnet suffered partial disintegration through some agent which left the topaz unaffected.

One specimen collected by the writer illustrates with unusual lucidity the crystallographic relations of the two minerals in this epigrowth. In this specimen four pairs of topaz crystals radiate symmetrically from a point which represents the termination of the crystallographic axis of the underlying garnet. Each pair indicates between them an edge of the $n(211)$ garnet face and to which they are nearly parallel. A third topaz crystal, completing what is practically an equilateral triangle on the $n(211)$ face, lies parallel to an edge of the $o(111)$ and $n(211)$ garnet faces. These three topaz crystals typify through their positions the three directions taken by all topaz on each garnet $n(211)$ face; furthermore the brachypinacoids $b(010)$ of all three crystals are parallel and represent a plane surface which coincides with the $n(211)$ face of the garnet. The relationships between the two minerals as shown in this specimen are of added interest when one realizes that the crystal form of the garnet is completely missing, and in its place nothing remains but an irregular, rounded surface.

Beryl

Only two specimens were found of the red beryl which has already been described from the Thomas Range.[8] One crystal was picked up loose; a second was found adhering to rough, opaque topaz. Both crystals are examples of the simple hexagonal prism terminated by the base. They are flattened parallel to the base

[6] Cahn, Lazard, *Beitr. f. Kryst. Min.*, Vol. **2**, pp. 7–9, 1919.

[7] Goldschmidt, V., and Schröder, R., *ibid.*, pp. 11–16.

[8] Hillebrand, W. F., *Am. J. Sci.*, Vol. **19**, pp. 330–331, 1905.

and consequently of tabular shape. The color is a pale cherry-red. Both crystals measure an eighth of an inch across the base and are about one-third as thick.

In general it should be noted that practically all the specimens found at this locality were picked up loose in the talus or scant, rocky soil. It indicates not only the thoroughness of the weathering in this region, but also leads one to believe that this locality has been visited seldom, if ever, by collectors in recent years.

Blasting was tried in several places but proved, with one exception, to be quite fruitless. A few wine-colored topaz crystals were obtained after one blast, and bixbyite was present on most of these as small cubes of a very brilliant luster.

An Occurrence of Rare-Colored Topaz

Less than a mile eastward from the bixbyite locality, a second ridge exposure of whitish-gray rhyolite was discovered. Rough, opaque topaz crystals are very plentiful here, but practically no bixbyite. A majority of the topaz possess a pale rose to rose-red color along each side of the crystal. A few small, transparent crystals were found to be rose-tinted throughout, and the beauty of these specimens, combined with the rarity of this color in topaz, makes them of particular interest.

Minute, black crystals of two distinct types were observed to be present on surfaces of many topaz from this locality. Some of these crystals appear to be of rhombohedral shape, and it is possible that they are hematite. Others are slender, vertically-striated prisms. Professor Charles Palache of Harvard University has kindly identified the crystals as pseudobrookite. This is the second reported occurrence of pseudobrookite in the Thomas Range, following Palache's earlier description in the preceding issue of this Journal.

The fact that both the rose color of topaz and presence of pseudobrookite are unique factors of this mineral occurrence, leads one to suppose that the rose color in the topaz may be due to the presence of titanium. It should be noted also that this rose color is not lost on exposure to light, as it is in the wine-colored topaz, for all the specimens described above were found weathered out of the rhyolite and fully exposed to the elements.

Acknowledgment

The writer wishes to express his indebtedness to Professor A. H. Phillips of Princeton University for invaluable assistance rendered throughout the preparation of the article.

BOOK REVIEW

LEERBOEK DER GEOMETRISCHE KRISTALLOGRAPHIE, door P. TERPSTRA, 302 pp., 263 figs., 1 colored plate. P. Noorhoff, Groningen, **1927.**

This book, published over five years ago, seems to have escaped the attention of many American crystallographers. It contains the lectures given by the author to first year students at the University of Groningen, Holland. This is not a mere compilation of unexplained facts, but a true text-book in the best sense of the word.

It is scientific. Practically all propositions stated are proved; very few steps are omitted; when the author thinks a derivation is too long to be given in full, he indicates the trend of the reasoning. Successful efforts are made to tie up new ideas to already known concepts. Methods involving too advanced mathematical prerequisites are deliberately replaced by more elementary demonstrations. A quantitative viewpoint prevails throughout, in details (size of a crystal) as in fundamentals (accuracy of measurements and computations, validity of geometrical laws and formulae). Also the historical aspect is given due consideration.

More specific remarks will show the stand taken by the author on a few debatable questions.

Although the deficiencies of Mallard's definition of a crystal (a homogeneous anisotropic body) are recognized, no substitute is offered. Friedel's very satisfactory definition is not given. This leads to an incomplete statement of the scope of geometrical crystallography, given as "the study of the laws controlling the crystal faces" (these laws also apply to the planes of the other *discontinuous vectorial properties*, such as cleavage, twinning, gliding, x-ray "reflections").

The treatment of stereographic projection is excellent. The statements of constructions and proofs are so interwoven that it is hard to find the "recipe" for solving a stereographic problem without understanding the demonstration. The old stumbling block that *two planes passed through the poles of two great circles cut off equal arcs from these two great circles* is given an illuminating demonstration by means of an excellent figure. One property, however, is implied, although neither proved nor postulated, namely, *the projection of a tangent to a curve is tangent to the projection of the curve*. The author recommends the Wulff net and favors the combined gnomonic and stereographic projections.

In the *law of rationality*, a commonly overlooked statement is brought out: If OA, OB, OC be the intercepts of the unit-face; OH, OK, OL, those of a face (*hkl*), then the ratios OH:OA, OK:OB, OL:OC need not be rational; all the law requires is that the ratios $\frac{\mathrm{OH}}{\mathrm{OA}}:\frac{\mathrm{OK}}{\mathrm{OB}}:\frac{\mathrm{OL}}{\mathrm{OC}}$ be rational (three examples illustrate this point). The validity of the law is well discussed. Although the author presents three different forms of the law (indices, zones, anharmonic ratio), he omits its geometrical expression by means of a space-lattice . . . the only way of grasping its full significance (reticular densities)! Many pages are devoted to the *complications* (Goldschmidt-Fedorov), an imperfect substitute for the Law of Bravais.

The symmetry symbols used are similar to those of Niggli and Schoenflies. No complete derivation of the 32 classes is attempted, but the essentials are given in the form of symmetry theorems. Terpstra uses one kind of alternating symmetry only, rotatory reflection.

The fifth chapter (zonal relations, transformation formulae) is one of the best in the book. As the student is not expected to know solid analytical geometry, the equation of a plane is derived by Cesàro's elementary method. Terpstra reduces most of the three-dimensional problems to questions of plane geometry by passing all planes through the point $z=c$. Cesàro's elementary derivation of the anharmonic ratio of four tautozonal faces is given. The duality principle is explained; "trimetric coordinates" are introduced. The old mnemonic rule of *cross-multiplication* ceases to be a magician's trick since enough is given about determinants and matrices for a logical derivation. The problem of teaching crystallography to students with scant mathematical background apparently can be solved!

In the description of crystal forms, the emphasis is laid on the derivation of forms from one another and also on the application of the Addition and Subtraction Rules. Terpstra sides with the opponents of merohedry, and yet manages to make use of the simplicity of merohedral derivations without patronizing merohedral nomenclature. Fedorov's idea of *isotropic zone* is introduced. A good feature is the table of forms of the isometric system with sketches showing the differences in the *face symmetry* of forms occurring in several crystal classes.

In the hexagonal system, the Bravais notation is adopted, and Weber's elegant four-index symbols are also preferred for zone notation. Both Miller and Bravais axes are used for the five classes of the rhombohedral subsystem.

The chapter on triclinic crystals contains interesting pages on the construction of the *rhombic section* in a stereographic projection, also the graphic determination of axial elements by means of a gnomonic projection.

Twelve pages are devoted to an elementary presentation of twinning, which exclusively reflects the tendencies of the German School. No heed is given to the remarkable explanation of twinning in terms of the space-lattice (the Mallard-Friedel theory).

Numerous exercises and problems are appended. The book is abundantly illustrated, well indexed, clearly printed, and solidly bound. It is gratifying that Dutch, of all languages, should be the most closely akin to English!

J. D. H. Donnay

MINERALOGICAL SOCIETY OF GREAT BRITAIN AND IRELAND

Anniversary Meeting, November 9th, 1933.

The following were elected officers and members of Council:—

President, Sir Thomas H. Holland; *Vice-Presidents*, Sir William H. Bragg and Mr. Arthur Russell; *Treasurer*, Mr. F. N. Ashcroft; *General Secretary*, Mr. W. Campbell Smith; *Foreign Secretary*, Prof. A. Hutchinson; *Editor of the Journal*, Dr. L. J. Spencer; *Ordinary Members of Council*, Prof. C. E. Tilley, Prof. P. G. H. Boswell, Prof. H. L. Bowman, Dr. L. Hawkes, Dr. W. R. Jones, Dr. F. Coles Phillips, Mr. J. B. Scrivenor, Mr. F. A. Bannister, Mr. T. Crook, Dr. W. F. P. McLintock, Mr. L. R. Wager, Dr. A. K. Wells.

Prof. P. L. Dravert (of Omsk): *Shower of meteoric stones in the neighbourhood of the village of Kuznetzovo, West Siberia, on May 26, 1932.* Between 5 and 6 P.M. in a cloudless sky ten detonations were heard, and one stone of 2 kg. was seen to fall, making a small oblique hole and then rebounding. Eight stones with a total weight

of 23 kg. (the largest 16 kg.) were collected. Two of them, found 300 metres apart, can be fitted together on their flat crusted surfaces. The stone is a greyish-white friable chondrite with inclusions of troilite and grains of nickel-iron. The troilite was thought by the peasants to be gold, which led to the destruction of some of the material.

Mr. P. A. Clayton and Dr. L. J. Spencer: *Silica-glass from the Libyan Desert.* Clear, greenish-yellow silica-glass has been found in considerable amount as wind-worn masses up to 10 lb. in weight over an area of 80 by 25 km. at about 500 km. S.W. of Cairo near the border of Italian Cyrenaica. It is found lying on the surface of the Nubian Sandstone in the "streets" between the north-south sand-dune ridges. Analysis by M. H. Hey shows, SiO_2 97.58% with small amounts of Al, Ti, Fe, Ca, Na, and a faint trace of nickel. Specific gravity 2.206, refractive index 1.4624 (sodium-light), hardness 6. Some pieces are cloudy, due to presence of minute (0.1 mm.) bubbles. Effective gem-stones have been cut from the material. It shows certain relations to tektites and also to the silica-glass from meteoric craters, but no craters have been recognized at the locality.

Dr. L. J. Spencer: *Fictitious occurrences of iron-silicide (ferrosilicon).* Bright, steel-grey nodules of iron silicide (FeSi), very resistant to acids (except HF) and to weathering, are sometimes present in the calcium carbide residues from acetylene lamps. This waste material has been found at times in strange situations, and has on two occasions been described as a new mineral. It has also been thought to be meteoric. Occurrences in the gold dredgings in British Guiana and in the diamond fields of South Africa are readily explained by the use there of acetylene flares.

Mr. Arthur Russell: *Notes on the occurrence of wulfenite at Brandy Gill, Carrock Fell, Cumberland; and of leadhillite at Drumruck mine, Gatehouse of Fleet, Kirkcudbrightshire.* Wulfenite occurs here in small ($1\frac{1}{2}$ mm.), honey yellow platy to scale-like crystals, often nearly circular in outline. Thirteen specimens were collected from an old trial level dump. Leadhillite, a single specimen showing six-sided tabular crystals, up to 5 mm. in diameter was collected during the working of the Drumruck mine in 1917.

Mr. Arthur Russell: *On the occurrence of harmotome at several new localities in the British Isles.* The occurrence of harmotome at the following mines is described: Snailbeach mine, Minsterley, Shropshire; Cwm Orog mine, Llangynog, Montgomeryshire; Settlingstones mine and Stonycroft mine, Fourstones, Northumberland; Whitespots mine, Newtonards, Co. Down, and Foxrock mine, Glendasan, Co. Wicklow.

Prof. C. E. Tilley and Mr. A. R. Alderman: *Progressive metasomatism in the flint nodules of the Scawt Hill contact zone.* The flint nodules of the Chalk of the Scawt Hill contact zone provide striking examples of progressive metasomatism. Various stages—of which analyses are given—from an original nodule composed wholly of quartz to an assemblage built up essentially of wollastonite, melilite and alkali-pyroxene can be traced. In the successive stages of replacement the characteristic shape and form of the nodules is preserved. The assemblages thus provide a particularly convincing illustration of a replacement process unaccompanied by volume change. The nature and source of the replacing solutions are discussed.

Dr. F. Coles Phillips: *Some relationships between the reflectivities of sulphide ore-minerals.* A review of the reflectivity data now available for a large number of opaque minerals has shown that the relative reflectivity of simple sulphides, selen-

ides and tellurides increases with atomic number. "Molecular refractivities" of over forty complex sulphides calculated from the measured reflectivities agree well with values computed from the "molecular refractivities" of the constituent simple sulphides, assuming additivity. This relation indicates a method of calculating the reflectivity of an ore-mineral and also affords a useful check on the specific gravity quoted in the literature. The "molecular refractivities" of sulphur, selenium, and tellurium calculated from reflectivities also agree with values derived from a study of transparent ionic compounds.

Dr. F. Coles Phillips: *A critical list of the specific gravities of the sulphides and allied ore-minerals*. Variations in the values of the specific gravities of ore-minerals quoted in the literature are due to misprints, determinations on impure material or mixtures, and actual variation in composition of specimens owing to solid solution. The probable correctness of a specific gravity determination can be checked by comparison of calculated and computed "molecular refractivities," by direct specific gravity determination of the synthetic mineral, and by the *x*-ray method. These criteria govern the author's choice of critical values, when correllated physical and chemical data on the same specimen are lacking. They are tabulated together with the maximum range of variation recorded in the literature.

NEWARK MINERALOGICAL SOCIETY

Eighteenth Annual Report of the Secretary (*Condensed*).

To the Members of the Newark Mineralogical Society:

The Eighteenth Annual Report of the Secretary of the Newark Mineralogical Society is presented, covering the fiscal year beginning November 1, 1932 and ending October 31, 1933.

Membership

On the roll, November 1, 1932	65	
Admitted to membership during the year	7	
Total		72
Lost during the year		2
On the roll October 31, 1933		70

Officers and Trustees

At the annual election on November 6, 1932 the following officers were chosen:

President: Louis Reamer of Orange, N. J.

Vice-President: Ernest A. Maynard of Brooklyn, N. Y.

Secretary: Herbert L. Thowless of Newark, N. J.

Treasurer: Herman M. Lehman of New Haven, Conn.

Meetings and Programs

During the past fiscal year the society has held eight regular monthly meetings, with programs, and a brief account of each meeting is given.

131st. meeting, November 6, 1932. Annual election of officers and trustees. Program, "The Inspection of Minerals under the Microscope." Microscopes furnished by Mr. Broadwell, Mr. Grenzig, Mr. Reamer and Mr. Walther.

132nd. meeting, December 4, 1932. Program consisted of a "Symposium on

Geodes." The Secretary exhibited the Neward Geode. Other exhibitors were Mr. Broadwell, Mr. Maynard and the President.

133rd. meeting, January 8, 1933. The program consisted of an illustrated talk by Dr. Horace R. Blank on "Observations in New York City's New Water Supply."

134th. meeting, February 5, 1933. The program consisted of a talk by Dr. Albert C. Hawkins on "Some Interesting Minerals of New Jersey," illustrated with many fine specimens.

135th. meeting, March 5, 1933. The program for the afternoon comprised a round table talk on "Minerals of California." Specimens were shown by the President, Mr. Broadwell, Mr. Grenzig, Mr. Milburn and Mr. Giordano.

136th. meeting, April 2, 1933. The afternoon was devoted to an illustrated talk by Dr. L. S. Wills, of Philadelphia, on "The Preparation of Micro Mounts."

137th. meeting, May 7, 1933. The program comprised a fine talk by Mr. Joseph F. Burke on the "Minerals of Staten Island." Mr. Ashby, Mr. Broadwell, Mr. Grenzig and others exhibited specimens.

138th. meeting, October 1, 1933. The subject for the meeting was a "Symposium on Summer Collecting" in which Mr. Maynard, Mr. Grenzig, the President and other members participated.

Respectfully submitted,
HERBERT L. THOWLESS,
Secretary

NEW HAVEN MINERAL CLUB

At the first meeting of the New Haven Mineral Club, organized by Lillian M. Otersen, and held on Sunday, December 17th, 1933, Mr. Frederick W. Fowler was elected acting Chairman. The following officers were then elected:

President: H. M. Lehman
Vice-President: Lillian Otersen
Treasurer: Charles Thomas
Secretary: Frederick S. Eaton

It was decided to hold the meetings on the third Monday of each month, starting with January 15th, 1934, at 8 P.M. at the Club House connected with East Rock Park Rose Gardens.

After the naming of the following committees: Program, Outing, Publicity and Membership, a tentative Constitution, and set of by-laws were proposed by President Lehman and accepted by the Club.

After the business meeting the club members held an informal gathering, and discussed their plans for the coming year.

Mr. Frederick S. Eaton gave an interesting talk on the different books and bulletins published covering the study of mineralogy and also the source of Connecticut minerals. Charles Thomas, Frank Wilson and Frederick Eaton also discussed their experiences in visiting different mineral localities in Connecticut, which proved most interesting.

LILLIAN OTERSEN, *Vice-President*